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Volume estimation from planform characteristics of washover morphology

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Key points

- Washover volume can be estimated from washover area
- Scaling relationships for washover size and shape link measurements from a physical experiment and real settings
- Estimation of washover volume from aerial imagery is a step toward quantifying storm-driven contributions to sediment budgets

Abstract

Overwash is the cross-shore transport of water and sediment from a waterbody over the crest of a sand or gravel barrier beach, and washover is the resulting sedimentary deposit. Washover volume, and alongshore patterns of washover distribution, are fundamental components of sediment budgets for low-lying coastal barrier systems. Accurate sediment budgets are essential to forecasting barrier system sustainability under future climate-driven forcing. However, comprehensive surveys of three-dimensional washover morphology are challenging to deliver. Here, we use the results of a physical experiment, analysis of lidar data, and examples of washover characteristics reported in the literature to develop scaling relationships for washover morphometry that demonstrate volume can be reasonably inferred from planform measurements, for washover in natural (non-built) and built barrier settings. Gaining three-dimensional insight into washover deposits from two-dimensional information unlocks the ability to analyze past aerial imagery and extract subaerial sand budgets for past storms.

Plain Language Summary

When a coastal storm drives water up and over the crest of a low-lying beach, sand – or gravel, in some places – gets picked up by the flow and deposited behind the beach. That deposit, which might settle among dunes, on a marsh, or on the streets of a neighborhood, is called washover. Knowing the total volume of washover delivered by a storm event helps coastal managers account for the amount of sediment that moves through a beach system over time, or a sediment budget. An accurate sediment budget provides an indication of environmental functioning and sustainability. However, washover volume is expensive to measure over large spatial scales – so despite its importance to sediment budgets, washover volume often goes unquantified. What if three-dimensional washover volume could be estimated from the two-dimensional shape and size of washover deposits visible in aerial photos? Here, we created washover deposits in a laboratory and compared them to real washover deposits to show that the area of a washover deposit is a good predictor of its volume. This relationship between area and volume unlocks information about past storm deposition captured in aerial photo archives, and enables rapid estimation of washover volume where direct measurement of volume is unavailable or impossible.

1. Introduction

A formative morphodynamic and evolutionary process of low-lying barrier coastlines is overwash (Leatherman, 1979; Donnelly et al., 2006; FitzGerald et al., 2008): the cross-shore transport of water and sediment from a waterbody over the crest of a sand or gravel barrier beach. The resulting sedimentary deposit left by overwash flow is termed washover (**Fig. 1**). Overwash is typical of storm events (Sallenger, 2000), but can occur under any conditions – including fairweather spring tides – in which a waterbody becomes super-elevated relative to the local beach or barrier crest, setting up sufficient hydraulic head to drive cross-shore flow (Fisher & Stauble, 1977; Donnelly et al., 2006; Kobayashi, 2010; Matias & Masselink, 2017). Washover volume and alongshore patterns of washover distribution are fundamental components of sediment budgets for barrier systems (Pierce, 1969; Leatherman, 1979; Nienhuis & Lorenzo-Trueba, 2019a, 2019b; Reeves et al. 2022). Sediment budgets are essential to forecasting barrier system sustainability or collapse under future climate-driven forcing (Lorenzo-Trueba & Ashton, 2014).

Despite the importance of washover volume as an empirical constraint, comprehensive surveys of three-dimensional washover morphology are challenging to deliver. Localized field studies of one or a few washover sites are relatively common in the coastal literature, but regional-scale analyses using remote-sensing tools are rare. One reason for that rarity is the availability – or unavailability – of three-dimensional data (i.e., digital elevation models) of sufficiently high spatial and temporal resolution to capture washover occurrence. Post-storm lidar surveys, for example, typically lack an anticipatory pre-storm survey with which to be compared: in some cases pre-storm baselines and post-storm surveys may be years apart (Sherwood et al., 2018; Williams & Rains, 2022) – where lidar is flown at all, let alone with any regularity. High-resolution structure-from-motion photogrammetry is emerging as a promising alternative resource for quantitative post-storm assessment, but for now remains computationally expensive (Sherwood et al., 2018, 2021).

Far more abundant than three-dimensional datasets is post-storm aerial imagery (**Fig. 1**) – particularly along the Atlantic and Gulf Coasts of the USA, thanks to the National Geodetic Survey Emergency Response Imagery program (National Geodetic Survey, 2022). Planform patterns of washover are readily observable in post-storm aerial imagery, motivating exploratory efforts to formalize scaling laws relating three-dimensional washover volume to measured characteristics of the two-dimensional washover planform (Overbeck et al., 2015; Rogers et al., 2015; Lazarus, 2016). However, scaling relationships derived from real settings have only attempted to link washover volume to cross-shore intrusion length (Overbeck et al., 2015; Rogers et al., 2015). This transect-oriented vantage aligns with way washover volume is commonly reported – not as the total volume of the whole deposit, but normalized as the volume per meter of cross-shore intrusion length (m^3m^{-1}), which is readily converted into a flux. (Carruthers et al. (2013) notes that this normalizing convention is inconsistently applied: some studies normalize washover volume by alongshore extent, which has the same units.) Washover volume (normalized or not) as a function of intrusion length tends to be a noisy relationship, dominated by scatter. Results of a physical experiment indicated that washover area could be a strong predictor of volume, and although the experimental deposits at

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the $\sim 10^{-1}$ m scale showed geometric and kinematic similarity to field-scale deposits (Paola et al., 2009), a relationship between volume and area was not tested for real settings (Lazarus, 2016).

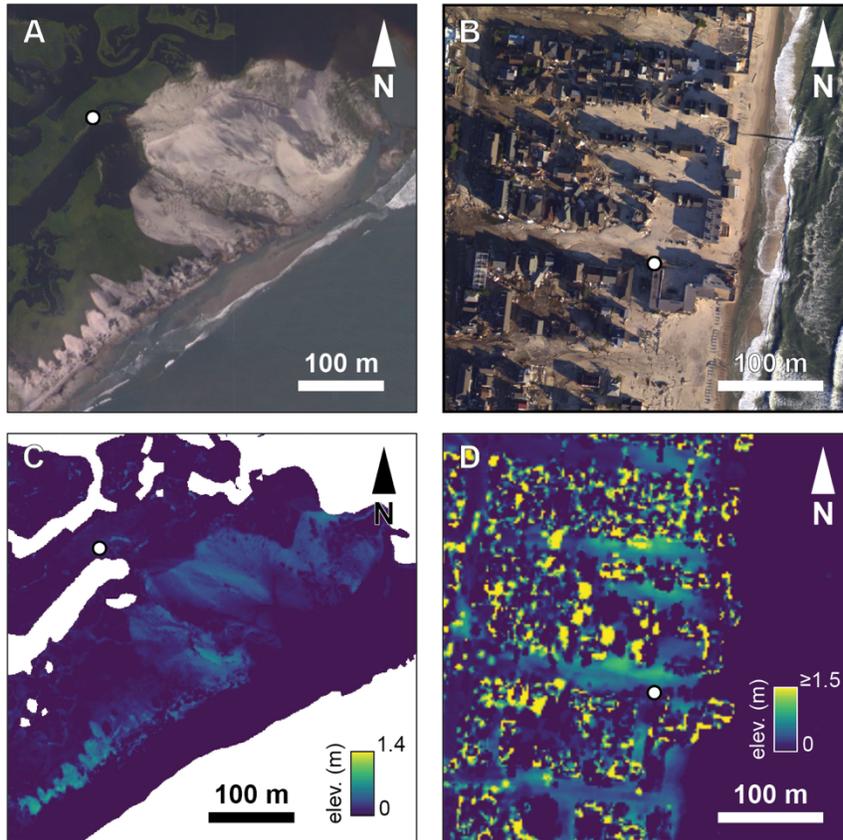


Figure 1. Examples of washover evident in post-storm aerial imagery from (a) natural (non-built) and (b) built settings, and (c, d) the equivalent deposits in lidar-derived, three-dimensional measurement of post-storm topographic change. White dots indicate same location in each image pair: (a, c) Onslow Beach, North Carolina, USA; UTM 18S 287034 m E, 3824707 m N; (b, d) Ortley Beach, New Jersey, USA; UTM 18S 579548 m E, 4423560 m N. Aerial imagery available from Emergency Response Imagery for (a) Hurricane Florence in 2017 and (b) Hurricane Sandy in 2012 (National Geodetic Survey, 2022). Lidar data available from NOAA Digital Coast (NOAA, 2022): (c) pre-storm: 2017 USACE NCMP Topobathy Lidar DEM: East Coast; post-storm: 2018 USACE NCMP Post-Florence Topobathy Lidar DEM: Southeast Coast; (d) pre-storm: 2012 USGS EAARL-B Lidar: Pre-Sandy; post-storm: 2012 USGS EAARL-B Lidar: Post-Sandy.

Furthermore, empirical scaling relationships for washover are complicated by the presence of built environments (Rogers et al., 2015; Lazarus et al., 2021), and by related human interventions in the intrinsic sediment pathways of barrier systems. In the USA, for example, many barrier systems are now intensively developed (Aldabet et al., 2022). Scaling relationships for planform characteristics of washover into built settings break at high built fractions (total building footprint per unit area), such

that washover in built and natural (non-built) settings become quantitatively distinct (Lazarus et al., 2021). Numerical models of barrier morphodynamics – coupling hydrodynamic forcing, sediment transport, and three-dimensional morphology – might produce realistic washover dynamics in natural barrier settings but perform poorly for built settings (Nienhuis et al., 2021). Initial empirical work has suggested that built environments may impart a scaling effect on washover volume (Rogers et al., 2015), but those findings – from cross-shore transects through a lidar-derived surface – only relate washover volume to intrusion length, and do not consider whole-deposit morphology. Nor can lidar be relied upon to record washover into built settings, because sediment (and other storm-driven debris) deposited on streets and roads is quickly cleared with earth-moving equipment to maintain emergency services (Nordstrom, 2003; Lazarus et al., 2021) – sometimes while deposition is actively underway (Lazarus & Goldstein, 2019). Aerial imagery may thus comprise the best record – and in most cases the only record – of washover deposition across natural and built barrier settings alike.

The circumstances of this data-dependent context prompts a basic question: What if three-dimensional washover volume could be estimated accurately from two-dimensional planform morphometry, in a variety of settings and at a range of spatial scales? How might that transform the utility of aerial imagery to enable more exhaustive empirical analysis of washover characteristics and patterns? Gaining three-dimensional insight into washover deposits from two-dimensional information unlocks the ability to analyze past aerial imagery and extract subaerial sand budgets for past storms – a key constraint for modelling, understanding, and managing barrier system sustainability (McNamara & Werner, 2008a, 2008b; Lorenzo-Trueba & Ashton, 2014; Miselis & Lorenzo-Trueba, 2017; Ashton & Lorenzo-Trueba, 2018; Nienhuis & Lorenzo-Trueba, 2019a; Passeri et al., 2020; Nienhuis et al., 2021; Reeves et al., 2022). Here, we use the results of a physical experiment, analysis of lidar data, and examples of washover characteristics reported in the literature to develop scaling relationships for washover morphometry that demonstrate volume can be reasonably inferred from planform measurements, for washover in natural (non-built) and built barrier settings.

2. Methods

2.1. Physical experiment

To generate a dataset of model washover morphology for comparison against remotely sensed observations at the field scale, we conducted a physical experiment that examined under controlled conditions how washover morphology manifest in non-built and built settings under the same forcing (**Fig. 2**). This experiment complements recent physical laboratory-based explorations of barrier dynamics, some of which have focused on cross-shore processes in gravel systems (i.e., BARDEX: Williams et al., 2012; Masselink et al., 2013), and others on morphodynamics in atoll motu systems (Tuck et al., 2019a, 2019b), subaerial delta fronts (Rodgers & Paola, 2021), and spatially extended barrier settings (Lazarus & Armstrong, 2015; Lazarus, 2016; Lazarus et al., 2020). (For a summary of early laboratory studies of overwash, see Donnelly et al., 2006.) Most physical models of overwash morphology are constructed as a shore-orthogonal barrier cross-section

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(Donnelly et al., 2006; Williams et al., 2012; Masselink et al., 2013), which highlights topographic changes in the beach and barrier profile but neglects lateral effects, whether at the scale of a single washover deposit (Williams, 2015; Rodriguez et al., 2020) or across many deposits in series (Lazarus and Armstrong, 2015; Lazarus, 2016; Lazarus et al., 2020; Rodgers & Paola, 2021). Here, we followed the premise of a previous physical experiment – smaller in scale by an order of magnitude – by Lazarus (2016), which produced barrier overwash morphology arrayed along a spatially extended, topographically uniform, non-built domain. We used an experimental design that is likewise spatially extended in the alongshore dimension, thus generating in each trial multiple washover features ($n \sim 10^1$) and a distribution of morphometric characteristics even under constant forcing.

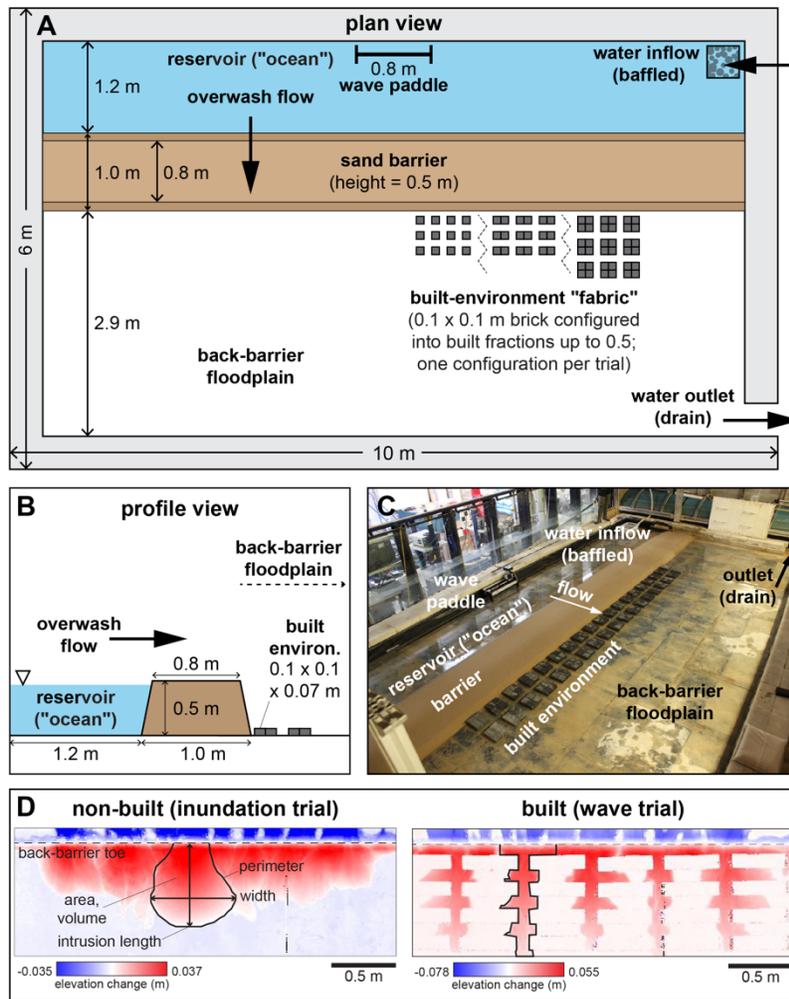


Figure 2. Experimental set-up in the Total Environment Simulator (TES) and representative resulting morphologies. Experimental schematic in (a) plan and (b) profile view; (c) oblique photo from inside the TES of a pre-trial set-up. (d) Examples of differenced topographic scans (final minus initial conditions) and resulting washover morphology from a non-built trial with inundation forcing (left) and built trial with wave-driven forcing (right).

This experiment ran in the Total Environment Simulator (TES) at the University of Hull (UK). The TES is a 6 x 10 m modular basin, fully enclosed on three sides with an outlet fully spanning one end of the flume to allow recirculation of water. Following the basic experimental design described by Lazarus (2016), we constructed a topographically uniform, low barrier (0.05 m height x 1 m cross-shore width x 10 m alongshore length) of sorted, medium sand ($D_{50} \sim 0.25\text{--}0.5$ mm) spanning the long dimension of the flume (**Fig. 2a–c**). Barrier uniformity and reproducibility was achieved by mounting a plywood template of the cross-shore profile to an overhead gantry, and running the template along the length of a loosely shaped barrier. The combination of a spatially extended alongshore dimension and low barrier elevation facilitates, in a given trial, the formation of many overwash sites and corresponding washover deposits (order $n \sim 10^1$) arrayed along the barrier. Moreover, a topographically uniform initial barrier with such a stretched aspect ratio – much as real coastal barriers are characteristically elongate in their alongshore dimension (Mulhern et al., 2017) – creates space for alongshore patterning of washover morphology (Lazarus & Armstrong, 2015; Lazarus, 2016; Lazarus et al., 2020).

To drive the overwash process, one side of the barrier (the "ocean" side) was gradually filled as a reservoir; discharge into the reservoir was held constant, and inflow was baffled using a box of cobbles. Overwash flow and washover deposition began once the water level in the reservoir exceeded the height of the barrier crest. The receiving side of the barrier (the "back-barrier floodplain" side) was left dry, and overwash flow was allowed to drain away. A trial ceased when sediment transport had effectively ceased (typically $\sim 20\text{--}25$ mins). The back-barrier floodplain was either left bare, to represent a non-built barrier setting, or was configured with blocks of bricks to represent a built setting. Brick units were gridded into different patterns to represent a range of built fractions (Lazarus et al., 2021), taken as the total footprint area of brick units relative to the total area built (including the open space between brick blocks – see **Fig. 2a**).

We tested two forcing regimes: one in which overwash flow is driven by still-water levels above the barrier elevation, mimicking barrier inundation (Lazarus, 2016); and one in which overwash flow is driven by wave overtopping (Sallenger, 2000). For inundation, inflow into the ocean reservoir was continuous (2.9 L s^{-1}) and water allowed to flow freely over the barrier. For wave-driven forcing, the seaward reservoir was filled with water to the height of the barrier crest, and then a small wave paddle (Emriver EM2 wave paddle; ~ 1.1 s period; ~ 0.01 m wave amplitude) used to push water over the barrier. The wave paddle was able to drive overwash across approximately 4 m of the barrier at a time; when sediment transport had effectively ceased in one half, the trial was paused, the paddle shifted to face the unworked half of the barrier, and the trial restarted.

The full barrier was scanned before and after a trial (drained) using an overhead-mounted terrestrial laser scanner to generate digital elevation models (resolution to within ~ 1.5 mm). The raw point-clouds were processed using the in-built software of the FARO laser scanner mounted in the TES. Taking the difference between the resulting digital elevation models to emphasise patterns of accretion, we manually identified and digitized 501 individual washover deposits and measured their

morphometric characteristics (**Fig. 2d**). Conditions for each experimental trial, along with all of the experimental data, are available from Williams et al. (2022).

2.2. Lidar analysis

We measured washover morphometry, including volume, for 148 deposits in natural (non-built) and built settings along the barrier coastline of New Jersey, USA, by taking the difference between lidar-derived digital elevation models (DEMs) bracketing Hurricanes Sandy (2012). We also collated 35 measurements of washover morphometry, including volume, reported in the literature by six different studies, sampling different storm events in different barrier settings (Carruthers et al., 2013; Williams, 2015; Rodriguez et al. 2020; Hansen et al., 2021; Williams & Rains, 2022), including a carbonate system (Jamison-Todd et al., 2020). Lidar surfaces were downloaded from the NOAA Digital Coast Data Access Viewer (NOAA, 2022). Geospatial analysis was done in QGIS version 3.22.5. We masked both the pre- and post-storm surfaces to isolate only positive elevations, and subtracted the pre-storm surface from the post-storm surface to calculate the difference between them; we then retained only the positive differences in the resulting surface to isolate sites of sediment deposition. We manually digitized the perimeters of depositional forms we interpreted as washover, corroborated by aerial imagery (National Geodetic Survey, 2022).

Basic geometric characteristics (perimeter, area) were taken directly from the washover polygons; washover length and width were taken from oriented minimum bounding boxes around each polygon. Volume for each washover polygon was measured using the Volume Calculation Tool (version 0.4) plugin for QGIS (REDcatch GmbH, 2022). In built settings, each washover deposit was associated with a locally estimated built fraction (Lazarus et al., 2021). Elements of the built environment (i.e., buildings) were isolated by creating a binary mask of the pre-storm surface, such that all elevations ≥ 5 m were set to a value = 1, and all elevations < 5 m set to zero. Minimum enclosing circles were drawn around each washover polygon, and the total built area (masked value = 1) within each circle summed using the QGIS Zonal Statistics tool. Here, local built fraction is the total built area within a minimum enclosing circle divided by the area of that circle. The geospatial data layers that we created, along with the resulting washover morphometry and references to the lidar surveys underpinning these data, are available from Lazarus et al. (2022).

3. Results & Discussion

Drawing on collated measurements of experimental and field-scale washover morphology, we formalize scaling relationships for deposit volume as a function of two primary planform characteristics: intrusion length (**Fig. 3a**) and deposit area (**Fig. 3b**). Of these two relationships, volume as a function of area reflects less variability in its distribution. Normalizing washover volume by intrusion length – and then plotting as a function of intrusion length, per convention – does not deliver as clear a scaling relationship because the three-dimensionality of the deposit gets negated: a transect might slice through a deposit near its lateral margin, and so return an anomalously low volume, or slice a deposit through its thickest region and reflect the maximum volume. Given that

washover deposits appear to exhibit allometric growth (Lazarus et al., 2020), such that dimensions of washover morphology are not just scaled relative to each other but change relative to each other in an organized way, our results indicate the importance of whole-deposit considerations in estimations of washover flux.

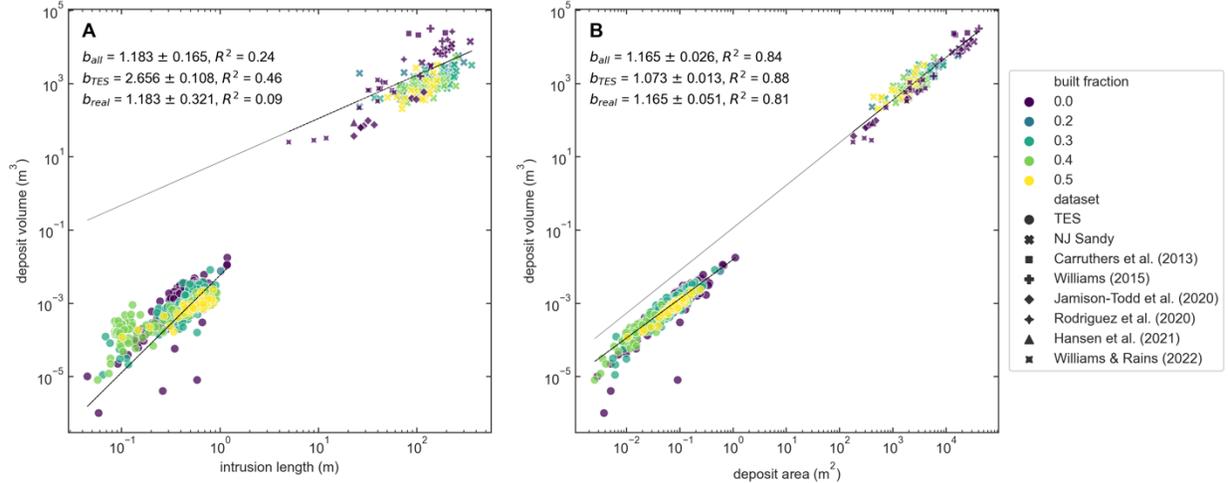


Figure 3. Scaling relationships for washover volume as a function of (a) length and (b) area, spanning the physical experimental results from the TES and real washover deposits from lidar analysis and examples reported in the literature. These results indicate that the best planform predictor of washover volume is area. Nonlinear regressions of the form $y = ax^b$ were performed in linear space; results are plotted in log-log space.

Unlike other scaling relationships between washover characteristics, such as any involving perimeter (Lazarus et al., 2021), washover volume as a function of area appears generally insensitive to built fraction. This is not to say that high built fraction has no effect on washover magnitude: a barrier with a high built fraction *ipso facto* has less accommodation space in which any deposition can occur. Where built fraction is high, sediment can only go down streets and between buildings. Yet while the planform shape of a washover deposit may become highly distorted, we find that the scaling relationship between area and volume is preserved. This relative insensitivity to built fraction suggests that area, specifically, may serve as a powerful predictor of washover volume in a wide variety of barrier environments. That is, rather than requiring different scaling relationships across a range of built fractions, volume as a function of area describes a single scaling relationship for all built fractions.

Overwash processes and washover formation are notoriously difficult to observe and record *in situ* (Leatherman & Zaremba, 1987; Engelstad et al., 2017, 2018; Matias & Masselink, 2017), and as long as three-dimensional surveys of post-storm impacts remain sparse, physical experiments can inform and corroborate numerical modelling of storm impacts on barrier systems (e.g., McCall et al. 2010; Rogers et al., 2015; Miselis & Trueba, 2017; Smallegan & Irish, 2017; Passeri et al., 2020; Nienhuis et al., 2021) and motivate testable hypotheses regarding future barrier dynamics. Something we were uniquely able to observe in the experiment is a marked morphological distinction between

inundation- and wave-driven washover (Fig. 4) – the two forcing regimes at the upper end of the Sallenger storm-impact scale (Sallenger, 2000). In the scaling relationship for volume as a function of area, the scaling exponents for the two forcing regimes are effectively indistinguishable (Fig. 4a), but inundation-driven washover consistently yielded more volume per unit area than wave-driven washover. A two-tailed Kolmogorov-Smirnoff test confirms that the experimental inundation- and wave-driven washover deposits represent statistically distinct distributions (Fig. 4b). Inundation-driven deposits in the experimental trials were perhaps thicker than their wave-driven counterparts because inundation manifested as an instantaneously deeper prism of cross-shore flow relative to wave forcing, capable of affecting greater sediment transport. The generic barrier system in this physical experiment was not supply-limited: there was more sediment available in the barrier than the forcings applied could transport. Future work could quantify how inundation and wave-driven forcing regimes shape washover morphology in real settings, and/or test different conditions of sediment availability. For example, a supply-limited system might produce the opposite result, wherein volume is retained in wave-driven washover but lost with inundation and potential breaching (Nienhuis et al., 2021). A broader avenue of future work might explicitly link dynamic allometry in washover to overwash hydrodynamics and mechanics of deposition, and thus address the gap, typical of empirical scaling relationships (Mackin, 1963), between the observation of scaling patterns in washover morphology and mechanistic explanations for them.

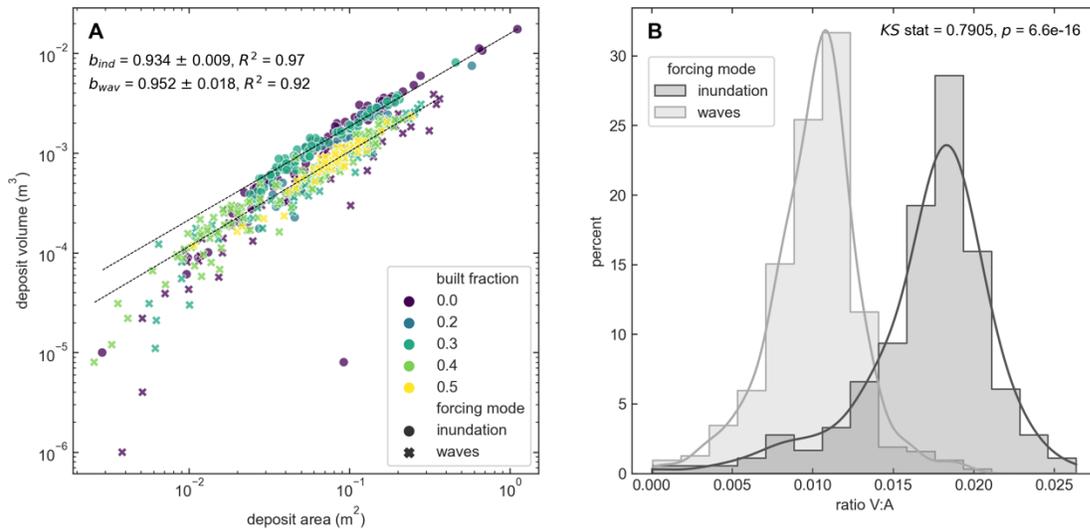


Figure 4. (a) *Scaling relationship for washover volume as a function of area, from the TES experimental results. Nonlinear regressions of the form $y = ax^b$ were performed in linear space; results are plotted in log space. Regressions for inundation and wave-driven forcing return approximately equivalent scaling exponents and are only shifted in log-log space by their coefficients, reflecting that (b) inundation forcing in the experiment yielded washover with greater volume per area than their wave-driven counterparts. These results suggest a scaling continuum between "overwash" and "inundation" regimes of the Sallenger (2000) storm impact scale for barriers.*

4. Implications

Our results suggest promising potential for using scaling relationships to estimate from remotely sensed imagery washover contributions to barrier system sediment budgets, in any barrier setting. Estimation of washover bulk volume from measurement of washover planforms evident in remotely sensed imagery could inform post-storm clean-up operations and quantify impacts to critical infrastructure, such as road networks (Kasmalkar et al., 2021; Velasquez-Montoya et al., 2021; Aldabet et al., 2022) – information relevant to planners and authorities responsible for emergency management, among other essential services. Paired comparisons between non-built and built barrier settings are a means of understanding how the latter function as geomorphic systems in their own right (Nordstrom, 1994), and how the two types of settings may evolve in divergent ways with changes in climate-driven forcing. Detailed qualitative descriptions of washover into built settings (Bush, 1991; Hall & Hallsey, 1991; Nordstrom 1994, 2004) are gradually being expanded upon with quantitative observations, particularly in the wake of hurricanes along the US Atlantic and Gulf coastlines (Morton & Paine, 1984; Morton et al., 2003; Rogers et al., 2015; Lazarus et al., 2021). How washover deposition into built environments affects and informs the evolution of human-altered barrier systems is largely unknown, as is how washover deposition into built settings should inform sediment budgets for predictive numerical models. Where and how much washover sediment gets redistributed by road crews during emergency clean-up operations remains unclear and unquantified (Lazarus & Goldstein, 2019). Washover sediment that gets plowed back to the upper beach profile and/or fronting dune may temporarily recharge the seaward face of the barrier at the expense of building elevation relative to sea level. Any washover sediment that does reach the back-barrier ultimately contributes to barrier transgression and persistence, but on more immediate time scales will likely appear to exacerbate shoreline erosion.

As post-storm observational datasets rapidly expand (National Geodetic Survey, 2022), so do opportunities to measure and investigate washover expression and morphology in its surprising variety (Morton & Paine, 1984; Morton & Sallenger, 2003; Williams, 2015; Goldstein et al., 2020, 2021). Motivated by scaling relationships like those we report here, future work should compare barrier washover patterns from as many different settings and contexts as possible (Matias et al., 2008; Ceia et al., 2010; Garcia et al., 2010; Stutz & Pilkey, 2011; Almeida et al., 2012; Carrasco et al., 2012; Mulhern et al., 2017; Kombiadou et al., 2019) – not only to generate a more comprehensive distribution of washover morphometrics, but also to identify where scaling relationships break, and under what conditions. Future experiments – physical and numerical – and more comprehensive empirical observation may test and refine the scaling relationships presented here, and further clarify fundamental controls on washover volume.

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Data and code availability

All datasets and analytical code used in this study are publicly available from the cited sources listed in the manuscript text.

Experimental datasets (Williams et al., 2022) and geospatial data layers (Lazarus et al., 2022a) are freely available. Our code to analyze washover morphometry is available on GitHub (<https://github.com/envidynxlab/Experiment-World.git>) and at Lazarus et al. (2022b).

This manuscript also relies on open data, specifically lidar datasets via the NOAA Digital Coast Data Access Viewer (<https://coast.noaa.gov/dataviewer/#/lidar/search/>).

Author Contributions (CRediT contributor roles)

EDL – conceptualization, investigation, methodology, formal analysis, writing, supervision, project administration, funding acquisition; HEW – investigation, methodology, formal analysis, data curation, writing; EBG – conceptualization, investigation, methodology, formal analysis, writing, funding acquisition.

References

- Aldabet, S., Goldstein, E. B., & Lazarus, E. D. (2022). Thresholds in road network functioning on US Atlantic and Gulf barrier islands. *Earth's Future*, *10*, e2021EF002581. <https://doi.org/10.1029/2021EF002581>
- Almeida, L. P., Vousdoukas, M. V., Ferreira, Ó., Rodrigues, B. A., & Matias, A. (2012). Thresholds for storm impacts on an exposed sandy coastal area in southern Portugal. *Geomorphology*, *143*, 3–12. <https://doi.org/10.1016/j.geomorph.2011.04.047>
- Ashton, A.D., Lorenzo-Trueba, J. (2018). Morphodynamics of barrier response to sea-level rise. In *Barrier Dynamics and Response to Changing Climate* (eds L. Moore and A. B. Murray). Springer, Cham., 277–304. https://doi.org/10.1007/978-3-319-68086-6_9
- Bush, D. M. (1991). Impact of Hurricane Hugo on the rocky coast of Puerto Rico. *Journal of Coastal Research*, *SI8*, 49–67.
- Carrasco, A. R., Ferreira, Ó., Matias, A., & Freire, P. (2012). Natural and human-induced coastal dynamics at a back-barrier beach. *Geomorphology*, *159*, 30–36. <https://doi.org/10.1016/j.geomorph.2012.03.001>
- 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>
- Ceia, F. R., Patrício, J., Marques, J. C., & Dias, J. A. (2010). Coastal vulnerability in barrier islands: The high risk areas of the Ria Formosa (Portugal) system. *Ocean & Coastal Management*, *53*(8), 478–486. <https://doi.org/10.1016/j.ocecoaman.2010.06.004>
- 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>
- Engelstad, A., Ruessink, B. G., Wesselman, D., Hoekstra, P., Oost, A., & van der Vegt, M. (2017). Observations of waves and currents during barrier island inundation. *Journal of Geophysical Research: Oceans*, *122*, 3152–3169. <https://doi.org/10.1002/2016JC012545>
- Engelstad, A., Ruessink, B. G., Hoekstra, P., & van der Vegt, M. (2018). Sand suspension and transport during inundation of a Dutch barrier island. *Journal of Geophysical Research: Earth Surface*, *123*, 3292–3307. <https://doi.org/10.1029/2018JF004736>
- 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>
- Fisher, J. S., & Stauble, D. K. (1977). Impact of Hurricane Belle on Assateague Island washover. *Geology*, *5*, 765–768. [https://doi.org/10.1130/0091-7613\(1977\)5<765:IOHBOA>2.0.CO;2](https://doi.org/10.1130/0091-7613(1977)5<765:IOHBOA>2.0.CO;2)
- Garcia, T., Ferreira, Ó., Matias, A., & Dias, J. A. (2010). Overwash vulnerability assessment based on long-term washover evolution. *Natural Hazards*, *54*(2), 225–244. <https://doi.org/10.1007/s11069-009-9463-3>

***** Please note that this manuscript is an EarthArXiv preprint and not yet peer-reviewed. This work is provided by the authors to ensure timely dissemination of scholarly work on a non-commercial basis. *****

Goldstein, E. B., Buscombe, D., Lazarus, E. D., Mohanty, S. D., Rafique, S. N., Anarde, K. A., et al. (2021). Labeling poststorm coastal imagery for machine learning: Measurement of interrater agreement. *Earth and Space Science*, 8, e2021EA001896. <https://doi.org/10.1029/2021EA001896>

Goldstein, E. B., Mohanty, S. D., Rafique, S. N., & Valentine, J. (2020). An active learning pipeline to detect hurricane washover in post-storm aerial images. *AI for Earth Sciences Workshop at NeurIPS 2020*. <https://doi.org/10.31223/X5JW23>

Hall, M. J., & Halsey, S. D. (1991). Comparison of overwash penetration from Hurricane Hugo and pre-storm erosion rates for Myrtle Beach and North Myrtle Beach, South Carolina, USA. *Journal of Coastal Research*, SI8, 229–235.

Hansen, L. Ø., Ernsten, V. B., Clemmensen, L. B., Al-Hamdani, Z., & Kroon, A. (2021). A method for estimating sediment budgets of washover deposits using digital terrain models. *Earth Surface Processes and Landforms*, 46(4), 804–821. <https://doi.org/10.1002/esp.5066>

Jamison-Todd, S., Stein, N., Overeem, I., Khalid, A., & Trower, E. J. (2020). Hurricane deposits on carbonate platforms: A case study of Hurricane Irma deposits on Little Ambergris Cay, Turks and Caicos Islands. *Journal of Geophysical Research: Earth Surface*, 125, e2020JF005597. <https://doi.org/10.1029/2020JF005597>

Kasmalkar, I. G., Serafin, K. A., & Suckale, J. (2021). Integrating urban traffic models with coastal flood maps to quantify the resilience of traffic systems to episodic coastal flooding. *MethodsX*, 8, 101483. <https://doi.org/10.1016/j.mex.2021.101483>

Kobayashi, N., Farhadzadeh, A., Melby, J., Johnson, B., & Gravens, M. (2010). Wave overtopping of levees and overwash of dunes. *Journal of Coastal Research*, 26(5), 888–900. <https://doi.org/10.2112/JCOASTRES-D-09-00034.1>

Kombiadou, K., Matias, A., Ferreira, Ó., Carrasco, A. R., Costas, S., & Plomaritis, T. (2019). Impacts of human interventions on the evolution of the Ria Formosa barrier island system (S. Portugal). *Geomorphology*, 343, 129–144. <https://doi.org/10.1016/j.geomorph.2019.07.006>

Lazarus, E. D. (2016). Scaling laws for coastal overwash morphology. *Geophysical Research Letters*, 43, 113–119. <https://doi.org/10.1002/2016GL071213>

Lazarus, E. D., & Armstrong, S. (2015). Self-organized pattern formation in coastal barrier washover deposits. *Geology*, 43, 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, 37–50. <https://doi.org/10.5194/esurf-8-37-2020>

Lazarus, E. D., & Goldstein, E. B. (2019). Is there a bulldozer in your model? *Journal of Geophysical Research: Earth Surface*, 124(3), 696–699. <https://doi.org/10.1029/2018JF004957>

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. <https://doi.org/10.1029/2020EF001818>

Lazarus, E. D., Goldstein, E. B., & Williams, H. E. (2022a). Washover morphometry: lidar-derived and reported in literature [data set]. *Zenodo*. <https://doi.org/10.5281/zenodo.6638548>

*** Please note that this manuscript is an EarthArXiv preprint and not yet peer-reviewed. This work is provided by the authors to ensure timely dissemination of scholarly work on a non-commercial basis. ***

- Lazarus, E. D., Goldstein, E. B., & Williams, H. E. (2022b). Code for 'Volume estimation from planform characteristics of washover morphology' [code]. *Zenodo*.
<https://doi.org/10.5281/zenodo.6641396>
- Leatherman, S. P. (1979). Migration of Assateague Island, Maryland, by inlet and overwash processes. *Geology*, 7, 104–107. [https://doi.org/10.1130/0091-7613\(1979\)7<104:MOAIMB>2.0.CO;2](https://doi.org/10.1130/0091-7613(1979)7<104:MOAIMB>2.0.CO;2)
- Leatherman, S. P., & Zaremba, R. E. (1987). Overwash and aeolian processes on a U.S. northeast coast barrier. *Sedimentary Geology*, 52, 183–206. [https://doi.org/10.1016/0037-0738\(87\)90061-3](https://doi.org/10.1016/0037-0738(87)90061-3)
- 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(4), 779–801. <https://doi.org/10.1002/2013JF002941>
- Mackin, J. H. (1963). Rational and empirical methods of investigation in geology. In *The Fabric of Geology* (eds C. C. Albritton, C. Freeman), Stanford, California, USA, 135–163.
- Masselink, G., Turner, I., Conley, D., Ruessink, G., Matias, A., Thompson, C., et al. (2013). BARDEX II: Bringing the beach to the laboratory—again! *Journal of Coastal Research*, 65, 10065, 1545–1550. <https://doi.org/10.2112/SI65-261.1>
- Matias, A., Ferreira, Ó., Vila-Concejo, A., Garcia, T., & Dias, J. A. (2008). Classification of washover dynamics in barrier islands. *Geomorphology*, 97(3-4), 655–674.
<https://doi.org/10.1016/j.geomorph.2007.09.010>
- Matias, A., & Masselink, G. (2017). Overwash processes: Lessons from fieldwork and laboratory experiments. In *Coastal Storms* (eds P. Ciavola and G. Coco), 175–194.
<https://doi.org/10.1002/9781118937099.ch9>
- McCall, R. T., De Vries, J. V. T., Plant, N. G., Van Dongeren, A. R., Roelvink, J. A., Thompson, D. M., & Reniers, A. J. H. M. (2010). Two-dimensional time dependent hurricane overwash and erosion modeling at Santa Rosa Island. *Coastal Engineering*, 57(7), 668–683.
<https://doi.org/10.1016/j.coastaleng.2010.02.006>
- McNamara, D. E., & Werner, B. T. (2008a). Coupled barrier island–resort model: 1. Emergent instabilities induced by strong human-landscape interactions. *Journal of Geophysical Research: Earth Surface*, 113(F1), F01016. <https://doi.org/10.1029/2007JF000840>
- McNamara, D. E., & Werner, B. T. (2008b). Coupled barrier island–resort model: 2. Tests and predictions along Ocean City and Assateague Island National Seashore, Maryland. *Journal of Geophysical Research: Earth Surface*, 113(F1), F01017. <https://doi.org/10.1029/2007JF000841>
- Miselis, J. L., & Lorenzo-Trueba, J. (2017). Natural and human-induced variability in barrier-island response to sea level rise. *Geophysical Research Letters*, 44(23), 11–922.
<https://doi.org/10.1002/2017GL074811>
- Morton, R. A., & Paine, J. G. (1985). Beach and vegetation-line changes at Galveston Island, Texas: erosion, deposition and recovery from Hurricane Alicia. Bureau of Economic Geology, Geological Circular 85-5.

***** Please note that this manuscript is an EarthArXiv preprint and not yet peer-reviewed. This work is provided by the authors to ensure timely dissemination of scholarly work on a non-commercial basis. *****

- Morton, R. A., & Sallenger, A. H. (2003) Morphological impacts of extreme storms on sandy beaches and barriers. *Journal of Coastal Research*, 19, 560–573.
- Mulhern, J. S., Johnson, C. L., & Martin, J. M. (2017). Is barrier island morphology a function of tidal and wave regime? *Marine Geology*, 387, 74–84. <https://doi.org/10.1016/j.margeo.2017.02.016>
- Nienhuis, J. H., Heijkers, L. G. H., & Ruessink, G. (2021). Barrier breaching versus overwash deposition: Predicting the morphologic impact of storms on coastal barriers. *Journal of Geophysical Research: Earth Surface*, 126, e2021JF006066. <https://doi.org/10.1029/2021JF006066>
- Nienhuis, J. H., & Lorenzo-Trueba, J. (2019a). Can barrier islands survive sea-level rise? Quantifying the relative role of tidal inlets and overwash deposition. *Geophysical Research Letters*, 46, 14613– 14621. <https://doi.org/10.1029/2019GL085524>
- Nienhuis, J. H., & Lorenzo-Trueba, J. (2019b). Simulating barrier island response to sea level rise with the barrier island and inlet environment (BRIE) model v1.0. *Geoscientific Model Development*, 12(9), 4013–4030. <https://doi.org/10.5194/gmd-12-4013-2019>
- National Geodetic Survey. (2022). Emergency response imagery. Retrieved from <https://storms.ngs.noaa.gov>
- National Oceanic and Atmospheric Administration (NOAA). (2022) Digital Coast Data Access Viewer. Retrieved from <https://coast.noaa.gov/dataviewer/#/>
- 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. (2004). Beaches and dunes of developed coasts (2nd ed). Cambridge University Press.
- Overbeck, J. R., Long, J. W., Stockdon, H. F., & Birchler, J. J. (2015). Enhancing evaluation of post-storm morphologic response using aerial orthoimagery from Hurricane Sandy, in Coastal Sediments 2015, edited by P. Wang, J. D. Rosati, World Scientific, Miami, Fla. https://doi.org/10.1142/9789814689977_0250
- Paola, C., Straub, K., Mohrig, D., & Reinhardt, L. (2009). The “unreasonable effectiveness” of stratigraphic and geomorphic experiments. *Earth-Science Reviews*, 97, 1–43. <https://doi.org/10.1016/j.earscirev.2009.05.003>
- Passeri, D. L., Dalyander, P. S., Long, J. W., Mickey, R. C., Jenkins, R. L., Thompson, D. M., et al. (2020). The roles of storminess and sea level rise in decadal barrier island evolution. *Geophysical Research Letters*, 47, e2020GL089370. <https://doi.org/10.1029/2020GL089370>
- Pierce, J. W. (1969). Sediment budget along a barrier island chain. *Sedimentary Geology*, 3, 5–16. [https://doi.org/10.1016/0037-0738\(69\)90012-8](https://doi.org/10.1016/0037-0738(69)90012-8)
- REDcatch GmbH. (2022). Volume calculation tool for QGIS3. Retrieved from https://github.com/REDcatch/Volume_calculation_for_QGIS3

***** Please note that this manuscript is an EarthArXiv preprint and not yet peer-reviewed. This work is provided by the authors to ensure timely dissemination of scholarly work on a non-commercial basis. *****

- Reeves, I. R. B., Goldstein, E. B., Moore, L. J., & Zinnert, J. C. (2022). Exploring the impacts of shrub-overwash feedbacks in coastal barrier systems with an ecological-morphological model. *Journal of Geophysical Research: Earth Surface*, 127, e2021JF006397. <https://doi.org/10.1029/2021JF006397>
- Rodgers, N., & Paola, C. (2021). Intermittent retreat behavior in experimental barrier island response to constant sea level rise and wave forcing. *Journal of Geophysical Research: Earth Surface*, 126(8), e2021JF006086. <https://doi.org/10.1029/2021JF006086>
- 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(12), 2609–2624. <https://doi.org/10.1002/2015JF003634>
- Rodriguez, A. B., Theuerkauf, E. J., Ridge, J. T. et al. (2020). Long-term washover fan accretion on a transgressive barrier island challenges the assumption that paleotempestites represent individual tropical cyclones. *Scientific Reports*, 10, 19755. <https://doi.org/10.1038/s41598-020-76521-4>
- Sallenger, A. H., Jr., (2000). Storm impact scale for barrier islands. *Journal of Coastal Research*, 16(3), 890–895.
- Sherwood, C. R., Dongeren, A. V., Doyle, J., Hegermiller, C. A., Hsu, T. J., Kalra, T. S., et al. (2021). Modeling the morphodynamics of coastal responses to extreme events: What shape are we in? *Annual Review of Marine Science*, 14(1), 457–492. <https://doi.org/10.1146/annurev-marine-032221-090215>
- Sherwood, C. R., Warrick, J. A., Hill, A. D., Ritchie, A. C., Andrews, B. D., & Plant, N. G. (2018). Rapid, remote assessment of Hurricane Matthew impacts using four-dimensional structure-from-motion photogrammetry. *Journal of Coastal Research*, 34(6), 1303–1316. <https://doi.org/10.2112/JCOASTRES-D-18-00016.1>
- Smallegan, S. M., Irish, J. L. (2017) Barrier island morphological change by bay-side storm surge. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 143(5), [https://doi.org/10.1061/\(ASCE\)WW.1943-5460.0000413](https://doi.org/10.1061/(ASCE)WW.1943-5460.0000413)
- Stutz, M. L., & Pilkey, O. H. (2011). Open-ocean barrier islands: global influence of climatic, oceanographic, and depositional settings. *Journal of Coastal Research*, 27(2), 207–222. <https://doi.org/10.2112/09-1190.1>
- Tuck, M. E., Ford, M. R., Masselink, G., & Kench, P. S. (2019a). Physical modelling of reef island topographic response to rising sea levels. *Geomorphology*, 345, 106833. <https://doi.org/10.1016/j.geomorph.2019.106833>
- Tuck, M. E., Kench, P. S., Ford, M. R., & Masselink, G. (2019b). Physical modelling of the response of reef islands to sea-level rise. *Geology*, 47(9), 803–806. <https://doi.org/10.1130/G46362.1>
- Velasquez-Montoya, L., Sciaudone, E. J., Smyre, E., & Overton, M. F. (2021). Vulnerability indicators for coastal roadways based on barrier island morphology and shoreline change predictions. *Natural Hazards Review*, 22(2), 04021003. [https://doi.org/10.1061/\(ASCE\)NH.1527-6996.0000441](https://doi.org/10.1061/(ASCE)NH.1527-6996.0000441)

***** Please note that this manuscript is an EarthArXiv preprint and not yet peer-reviewed. This work is provided by the authors to ensure timely dissemination of scholarly work on a non-commercial basis. *****

Williams, H. E., Lazarus, E. D., & Goldstein, E. B. (2022). Data and morphometric results from a physical experiment simulating washover deposition [data set]. *Zenodo*, <https://doi.org/10.5281/zenodo.6640209>

Williams, H. F. L. (2015). Contrasting styles of hurricane Irene washover sedimentation on three east coast barrier islands: cape lookout, North Carolina; Assateague Island, Virginia; and Fire Island, New York. *Geomorphology*, *231*, 182–192. <https://doi.org/10.1016/j.geomorph.2014.11.027>

Williams, H. F. L., & Rains, B. J. (2022). Effect of Barrier Height on Magnitude and Character of Hurricane Harvey Washover Fans, Matagorda Peninsula, Texas, USA. *Journal of Coastal Research*, *38*(1), 133–139. <https://doi.org/10.2112/JCOASTRES-D-21-00043.1>

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>