3D Morphodynamic Visualizations of Storm Impacts for Decision Support

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Abstract: 3D flood visualizations are commonly used by coastal managers and other experts to engage the public regarding storm impacts, and to support management decisions. 3D flood visualizations do not, however, capture physical changes to the landscape, such as erosion, that result from storms and do significant damage to human habitations and change ecological systems. We address this gap by presenting novel 3D morphodynamic visualizations that depict physical changes to the coastal morphology wrought by modelled storms. We propose these visualizations may be more effective than flood visualizations as decision support tools in situations where shoreline change is a factor. We describe the process of creating the visualizations for storm, sea level, and mitigation scenarios and make observations of their possibilities and limitations. The visualizations plainly show profoundly different outcomes than flood visualizations for the same storm. These visualizations may be extremely useful in the sedimentary contexts considered. However, the lack of clear conventions and complexity of creating these visualizations means that more experimentation is required before such visualizations can be considered for wide application.

Keywords: Shoreline change, landscape change, storm surge, sea level rise, visualization

1 Introduction

Hurricanes (tropical cyclones) and nor'easters (extra-tropical cyclones) present increasing uncertain risks to ecosystems and coastal communities in the Northeast United States. Nor'easters often occur in the fall, winter, and early spring, when shoreline sediments have been moved offshore by winter wave action (BOOTH et al. 2015, RANGEL-BUITRAGO AND ANFUSO 2011). These storms are thus powerful drivers of shoreline change because they erode and over-wash dunes, redistributing sediments. This process gradually modifies coastal barrier islands as the shoreline retreats (CONERY et al. 2018). Impacts to ecological systems vary. Storms may do damage to some ecological resources. Storms may also elevate marsh platforms through sediment deposition and refresh coastal lagoons by cutting new inlets allowing for water exchange, causing net positive effects (GOBLER et al. 2019, OLIN et al. 2020). Impacts to infrastructure, and private property occur through a range of mechanisms, including storm surge, waves, and erosion of land, in addition to flooding, wind, and secondary hazards such as power outage and obstructed emergency access among others (STEMPEL et al. 2018). This diversity of constructive and destructive impacts is not directly shown in conventional flood visualizations and can only be inferred.

We hypothesize that visualizing flooding alone likely results in an understatement of impacts, especially in sandy coastal barriers, because flood visualizations do not faithfully capture the extent of landscape change wrought by storms. Sedimentary coastal barrier systems such as

Journal of Digital Landscape Architecture, 8-2023, pp. 554-563. © Wichmann Verlag, VDE VERLAG GMBH · Berlin · Offenbach. ISBN 978-3-87907-740-3, ISSN 2367-4253, e-ISSN 2511-624X, doi:10.14627/537740058.

this comprise about 10 % of the world's coastlines (STUTZ AND PILKEY 2011). Flood visualizations of the likeliest scenarios, such as nor'easters and storms that have generally greater than 1 % chance of annual exceedance, may not show dramatic flooding at all, but nonetheless could result in significant impacts through shoreline change. The 1 % chance of exceedance storm is significant because it is the standard that many flood maps and assessments use, such as the US Federal Emergency Management Agency (HORN AND BROWN 2017). Flood visualizations also make it difficult to assess the efficacy of mitigation measures such as vegetation restoration or implementation of offshore reefs that reduce the effect of wave energy but have less visible effect on flooding.

Testing this hypothesis requires the development of a meaningful alternative to 3D flood visualization that can sincerely represent impacts and depict the effects of mitigation measures. To that end, this paper presents a novel workflow for a set of model-driven 3D morphodynamic visualizations that depict changes to the landscape wrought by storms and test the effects of several mitigation scenarios. These visualizations are being developed and used as decision support tools for communities, the US Fish and Wildlife Service, and other non-profit partners. We summarize the methods, present the visualizations, and observations and next steps based on the first application.

1.1 Project Site

This research is being conducted in South Kingstown and Charlestown Rhode Island, USA, two communities on a south facing coastline open to the Block Island Sound and the Atlantic Ocean. The geography consists of sandy coastal barriers and lagoons that support a rich ecology and vibrant coastal communities. The Ninigret Trustom National Wildlife refuge managed by the US Fish and Wildlife Service forms a significant part of the study area, and habitat conservation, especially for shore birds such as plover is a significant concern as is the diversity of the coastal ecosystem spanning a gradient of habitats from the intertidal zone, dunes, salt marshes, lagoons, and coastal shrub and woodlands. Initial management concerns included decisions regarding managing vegetation such as invasive species, and performance of a permanent breachway (constructed in 1958) with coastal structures damaged by Superstorm Sandy (2012). Other issues included prevalence of future breaching of the barrier system more broadly, the potential damage caused by successive storms, and extent of habitat zones for shorebirds.

2 Methods

The process for developing the 3D morphodynamic visualizations is following an approach that allows interested parties shape both visualization outputs and modeling decisions in a coherent, iterative process (STEMPEL AND BECKER 2019). This approach to developing hazard visualizations allows for significant exchange and calibration of information regarding risk and uncertainty between persons with differing levels and types of expertise and varied backgrounds through constant feedback (STEMPEL AND BECKER 2019, SALTER et al. 2010). In practical terms, this involved several steps: elicitation of management concerns and desired storm scenarios, measurement of existing conditions, modeling of water levels and wave heights, implementation of the morphodynamic models, and visualization. This was undertaken with frequent contact between interested parties and team members. Each of these steps is summarized in turn.

2.1 Management Concerns and Scenarios

Superstorm Sandy was selected as the *basis* for the initial storm scenarios. The team refers to the modelled storm as a "Sandy-like" scenario because current morphological conditions and application of sea level scenarios necessarily change the dynamic conditions of the models as compared to conditions present in 2012. An important note regarding the magnitude of Superstorm Sandy is that although Superstorm Sandy significantly affected coastal Rhode Island, USA (sustained windspeed of 111 kmh, 69 mph), impacts were less severe than those to New York and New Jersey, USA (sustained windspeed of 177 kmh, 110 mph), further to the south where the center of the storm made landfall. Although Superstorm Sandy began as a hurricane (tropical cyclone), it made landfall as an extremely wide post-tropical cyclone with many of the characteristics of large nor'easters (extra-tropical cyclones) while retaining its tropical cyclone core (HALVERSON AND RABENHORST 2013). The majority of shoreline change in the Northeast USA is driven by nor'easters (extra-tropical cyclones) by virtue of their duration, size, and varied patterns of wave energy (HARLEY et al. 2017).

Three variations were tested with a Sandy-like storm under current sea levels and with an additional .33m of sea level incorporated into the models: current conditions, optimal vegetation cover, implementation of a segmented offshore coastal barrier. The coastal barrier is a complex topic not discussed here for reasons of brevity.

2.2 Measurement of Existing Conditions

The recency of geographic information becomes a significant factor in assessing sedimentary coastlines like the southern coast of Rhode Island, USA, because the starting condition is changing seasonally and annually, and is not in equilibrium (OAKLEY et al. 2019, HOLLIS et al. 2016). A 1-meter topobathy DEM was created from a combination of recent LiDAR and SoNAR data sources using older data to fill gaps between more recent scans. NOAA and USGS LiDAR data from 2018, 2014, 2012, 2011, and 2010 and aerial imagery from 1958 to the present was analyzed in combination with sediment sampling to understand both shoreline and vegetation changes and physical modifications to the system. This was complimented by terrestrial LiDAR gathered with a Trimble X7 terrestrial scanner.

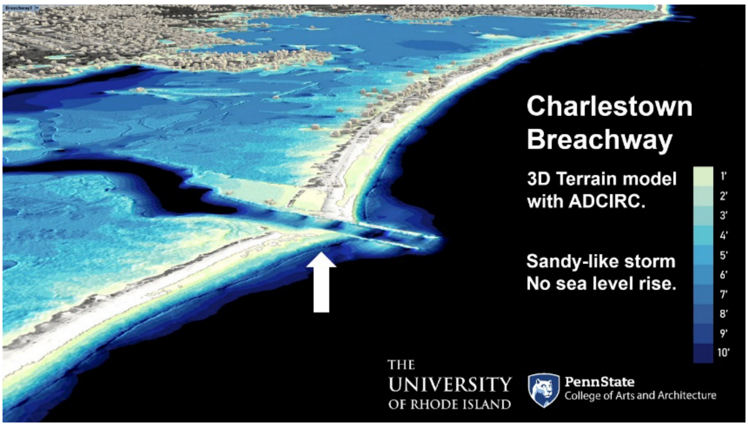

Fig. 1: 3D visualization of flooding modelled using ADCIRC. The arrow points to an area that will breach, as shown in Figure 3 and was used to orient audiences.

2.3 Water Levels and Wave Heights

Water levels and wave heights were assessed for the selected scenarios using the coupled ADvanced CIRCulation (ADCIRC) and Simulating Waves and Nearshore (SWaN) (ATKINSON et al. 2004, LUETTICH JR et al. 1992). ADCIRC uses an unstructured grid that has higher resolution in the nearshore area and wider node spacing in open ocean (Figure 1). ADCIRC SWAN outputs were used as a boundary condition for subsequent modelling.

2.4 Morphodynamic Modeling

Morphodynamic modelling simulates the interaction between sediments and hydrodynamic conditions, updating them continuously with the storm propagation. This was accomplished using the Xbeach model (ROELVINK et al. 2009) in a high-resolution coastal grid forced in boundary conditions by the results of the larger scale simulations with ADCIRC-SwaN (Figure 2). Xbeach was used in the "Surfbeat" mode to predict the morphodynamic changes occurring (throughout storm events (GRILLI et al. 2020).

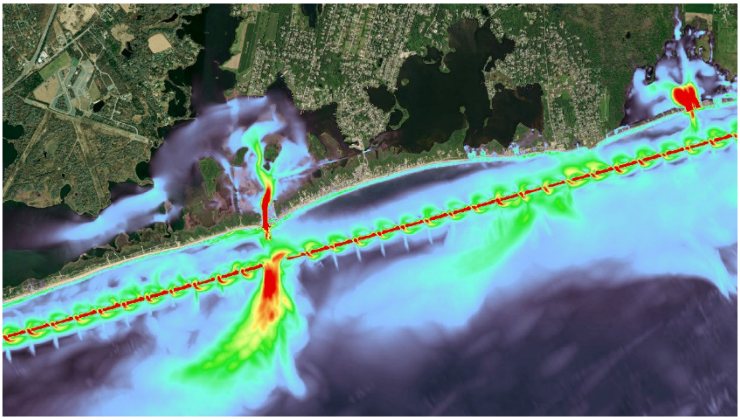

Fig. 2: An exploration of X-Beach outputs made using ArcGIS Pro. This scenario depicting water velocity includes the shore parallel coastal barrier (submerged reef).

2.5 Visualization

Space delimited tables were produced for model intervals representing the xy coordinates for each node, terrain, base flood elevation and water velocity. These were first explored in ESRI ArcGIS Pro so that the team could better understand the outputs. Tables used for 3D visualization were post-processed using python scripts. Data was organized to create xyz point clouds that could be read directly by McNeal Rhino. Colour ramps were applied to the data such that finished jpeg images could be generated directly from python, avoiding time consuming manual steps in GIS or other raster processing software.

Elevation data was coloured using a colour ramp reminiscent of world maps to allow for easy comparison of before and after conditions. Several unique graphic choices were made. These included treating base flood elevation as a 3D surface and mapping water velocity onto that surface and using a highly distinctive red-light yellow colour ramp to distinguish velocity from more conventional flood depth maps.

These outputs were combined with other geographic information in Rhino, and renders were created using conventional rendering processes in that platform. All steps were designed with future automation both inside and outside the rendering platform in mind to allow for production of animated sequences. An initial presentation was made using still visualizations presented in sequence (Initial visualization was completed quickly, with days between model output and presentation).

3 Results

The modelling and visualizations plainly demonstrated the significant impact of a Sandy-like storm should it occur under today's morphological conditions that have already been altered by Superstorm Sandy and subsequent smaller storms. Impacts included significant breaching of the barrier system, erosion behind fixed structures protecting structured breachways (openings between the lagoon and the open ocean) (Figure 3).

Fig. 3: Comparison of the condition of Charlestown Breachway before and after storm (0 SLR scenario). Compare to Figure 1.

Modelling and visualizations demonstrated that dune vegetation did make a significant difference in overtopping of the dune during storm events, potentially reducing damage and impacts, and supporting the further study and implementation of improvements to these nature-based systems (Figure 4). Implementation of the shore parallel reef did reduce storm impacts but did not prevent breaching. As seen in figure 2, the segmented nature of the barrier also introduced the potential of rip currents between segments, a potential hazard for recreational uses.

4 Observations and Next Steps

Visualizations were presented to local interested parties on October 27, 2022. This group included local council and committee members, representatives of US Fish and Wildlife Service, National Park Service, and non-profit organizations involved in coastal management. Some audience members were noticeably stunned by seeing the transformation of the landform. Interested parties were highly engaged, scrutinizing details, for instance, rapidly pointing out the mislabelling of a coastal pond. Persons who managed the breachway remarked that the effects on the storm were as expected but felt that the visualized outcomes clarified their understanding of the extent of the change. Visualizations of vegetation helped to express

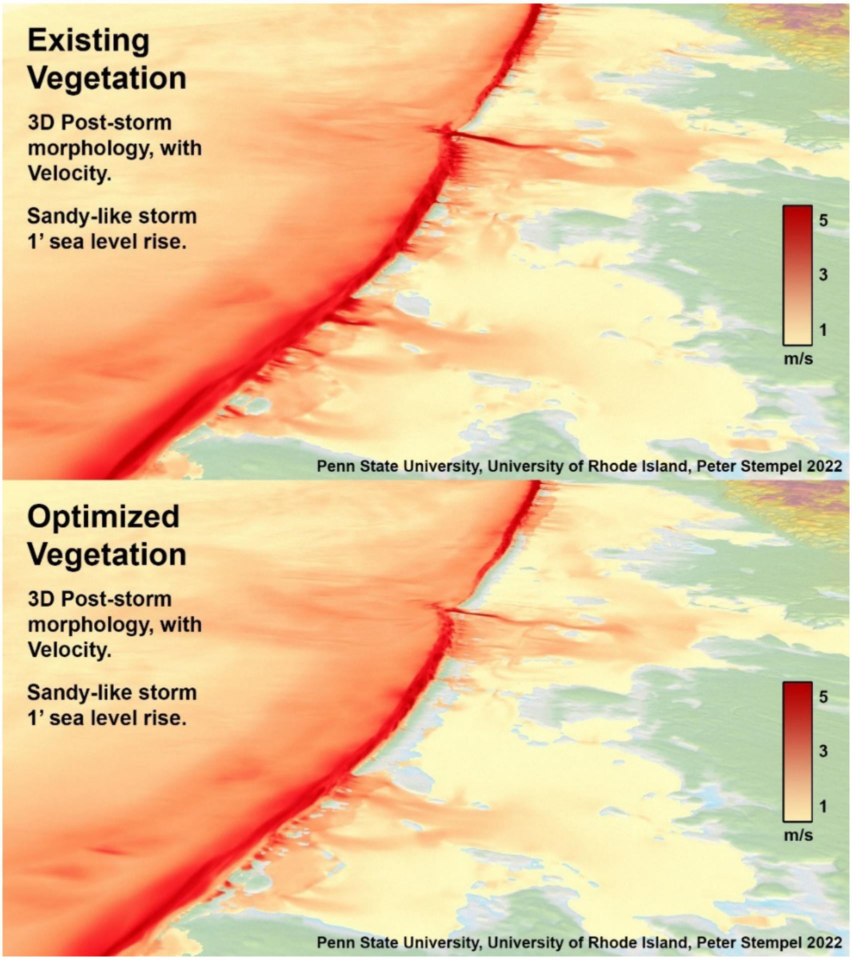

Fig. 4: Comparison of dune overtopping (mapping water velocity maximum on top of 3D flood elevation using existing and optimized vegetation (.33m / 1' SLR scenario)

a relative magnitude of potential effect of vegetation without promising protection. Unpacking the meaning of model choices such as "optimized vegetation" helped managers understand both limitations and possibilities for how modelling can inform decision making. The literature suggests that this kind of interaction bolsters both the perceived legitimacy and acceptance of modelled outcomes (e. g. WHITE et al. 2010).

The complexity of the modelling and effective characterization of outcomes would not have been possible without the implementation of a highly engaged and collaborative process. Weekly meetings of the project team and continual engagement with interested parties not only ensured that the team was coordinated with and understood each other and interested parties but aided with the communication of epistemic uncertainty related to model choice in addition to the aleatory uncertainty associated with the physical processes (MERZ & THIEKEN 2009). Repeated, open discussions of modelling choices also helped to reduce the "crystalizing" effects of visualizations that can make an outcome appear fixed or more certain than it is (DEITRICK & EDSALL 2009). For instance, we elected not to show structures such as houses in these first iterations of the morphodynamic visualizations simply because more experimentation is needed to determine how to effectively represent them without implying outcomes. Instead, this information was included in separate visualizations using identical viewpoints.

The crystalizing effects of visualizations seem particularly relevant in the case of morphodynamic visualizations because physical conditions continue to change and evolve throughout the model timespan and beyond. The still visualizations presented here can show a maximum change or a snapshot in time but fail to capture the continued evolution of the barrier in the aftermath of a storm that continually reshape a barrier breach (something that will be resolved by animation). Thus, effectively characterizing the exact nature of what was being shown required careful attention of modelers and visualizers working in tandem with interested parties. For instance, "velocity" being used as a proxy for the intensity of the storm impact because it could be visualized (Figure 5). Waves, however, are the predominant damaging hazard, and it would be ideal to represent them directly. These issues will persist until subsequent modelling is performed to better describe the phenomena. (GRILLI et al. 2020).

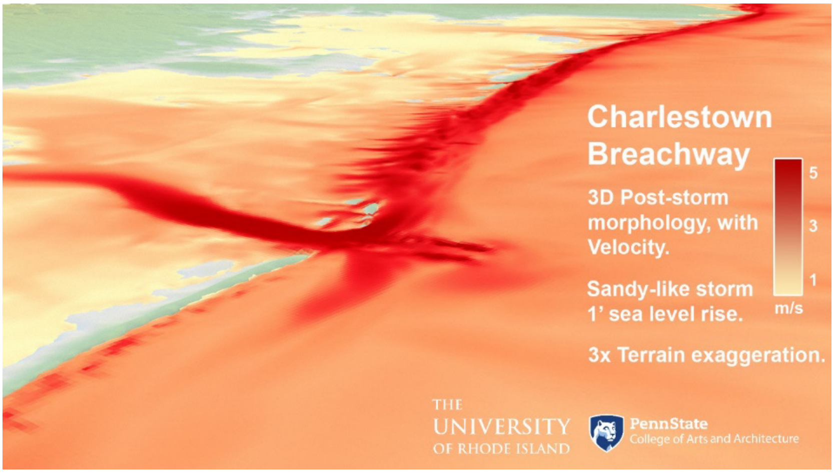

Fig. 5: Maximum water velocity mapped onto max flood elevation in the same view as Figures 1 and 3 (.33m / 1' SLR scenario)

The representational uniqueness of the still visualizations also necessitated extreme care in presentation. The project team used visualizations in sequences that oriented interested parties to the physical geography first, before proceeding through sequences of visualizations, keeping each set of visualizations in the same order. Further attention to issues such as the use of terrain exaggeration, inclusion of structures and orienting features, and developing consistent standards for colour ramps is essential. The absence of conventions and rapid timeframe of visualization development highlighted the value of familiar conventions in orienting audiences to what they were seeing.

Fig. 6: Example of a series of visualizations used to help orient audiences to the unfamiliar impact visualizations. Compare the effect to figure 4 without context.

We thus conclude that morphodynamic visualizations offer both possibilities and challenges. Anecdotal evidence suggests that they can be extremely effective in engaging interested parties in management decisions by depicting tangible storm impacts and effects of mitigation. Significant challenges exist, however, such as the development of repeatable paradigms for using these visualizations, and in the extent of coordinated expertise and engagement necessary to create and apply them. We are continuing development of these visualizations in this site and an additional site on Cape Cod, Massachusetts USA with the intention of doing more comprehensive experimental testing of these visualizations.

Acknowledgements

This work is part of a larger four-year project "Modeling, Visualizing, and Communicating Nor'easter and Hurricane Threats with Sea-Level Rise to Support Coastal Management Within New England". NOAA grant # NA-21-NOS4780149. This project examines management decisions that span National Parks, Monuments, Wildlife Refuges and adjacent communities in Rhode Island, Massachusetts and Maine, and is explicitly designed to use visualizations to operationalize state of the art ocean modelling for decision support.

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