MODELING COASTAL SEDIMENTATION AND EROSION FOR DESIGN APPLICATIONS WITHIN THE FIELDS OF LANDSCAPE ARCHITECTURE AND ARCHITECTURE

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Abstract.—Uncertainty of future coastline geophysical conditions is increasingly magnified by the growing severity of acute and chronic weather events induced by climate change. In the face of these threats, 21st century coastal-human relationships will be characterized by temporality, response and recovery, and restoration. Understanding these dynamics will require visual exploration and application of theoretical conditions to future scenario generation. This research examines the development of an interdisciplinary three-dimensional visual modeling methodology to simulate erosion, storm surges, and sea level rise of a beach community in southern Rhode Island. Using historic data of coastal conditions for Misquamicut, Rhode Island, the researchers identified patterns of coastal change to model and simulate future shoreline conditions that incorporate local hydrological dynamics. The resulting sedimentation and erosion patterns were translated into an emergent modeling methodology that landscape architects and allied professionals could use to test a design concept through iterative, accurate portrayals of environmental systems.

INTRODUCTION

This project involves the creation of a workflow intended to simulate coastal conditions using three-dimensional (3D) modeling and geographic information systems (GIS) software. The purpose of this project is to devise new methods of accurately simulating interrelated natural phenomena, in order to project future scenarios upon a coastal area. These processes—including wind, erosion, water movement, and the spread of vegetation—can generally be understood as acting within a range of natural variation and predictability. Yet when combined as an ecological system, they may dynamically interact in ways that elude digital capture and simulation.

Landscape architecture does not have a single method or best practice for designing within the highly unpredictable parameters of coastal flux, which is rendered even less predictable by the specter of sea level rise. Software enables rapid site analysis of existing conditions and allows the designer to execute design ideas with ease. There is a gap between these two stages of analysis and design, where the landscape architect must attempt to understand the natural forces that may act upon the design site at any point in the future and respond accordingly with the design concept. It is this territory—between analysis and design—which this project inhabits.

The Need for New Software Workflows

Twenty-first century landscape architects face challenges of enormous complexity that demand increasingly sophisticated software workflows. Rising population density in coastal areas, coupled with an imperative to design resilient landscapes that can tolerate extreme weather events, requires adaptation of traditional design processes. This adaptation necessitates technology that can quickly respond to complex parameters and illustrate their potential outcomes in visually meaningful ways that can then be interpreted by designers. Taking into account the large number of variables and algorithms embedded in the behavior of coastal ecological systems, a single software application is unlikely to capture their behavior in its entirety. Rather, a digital workflow is needed for these tasks—a series of digital processes that passes information from one piece of software to another in a prescribed manner.

Digital media in landscape architecture has historically provided computer-aided design (CAD) workflows which establish formal elements within the design such as spatial dimensions, materials, and quantities. 3D modeling software has augmented this process

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and enabled further rapid iteration of spatial design ideas. The introduction of GIS software has broadened the CAD workflow to include geospatial aspects; currently, there is a strong and established workflow interoperability between CAD and GIS software (Cureton 2017). This interoperability facilitates analysis of existing conditions as well as testing of three-dimensional (3D) design ideas; for example, performing a viewshed obstruction analysis with ESRI's Spatial Analyst. Landscape architects also now have access to tools that enable reconstruction of terrain from LiDar and aerial imagery. These tools enable us to document existing site conditions and test very simple design interventions to understand their impact from a visual perspective.

Advances in Digital Simulation

Design clients are increasingly demanding evidence of design performance outcomes in the form of digital simulations, which have historically been the territory of engineers. In the field of architecture, building information modeling (BIM) fulfills this function by embedding information into 3D models, enabling improved planning and project delivery. It is imperative that landscape architects adopt intelligent 3D modeling processes, BIM or otherwise, enabling the design process to become situated between analysis and formation. However, landscape architects will need to develop their own processes to overcome software shortcomings that do not address the complexity and irregularity of landscape geometry or the agency and flux of the natural systems where interventions will be applied. Research has shown a crucial need to position digitally proficient designers at the outset of a project to address these factors, creating "toolmakers" who enable software proficiency to inform all stages of the landscape design process (Walliss and Rahmann 2016).

Some computational design researchers have begun to address this territory, developing algorithms that emulate and visualize the behavior of natural systems. An early precedent is "The Algorithmic Beauty of Plants," which presents fractal assembly methods that effectively simulate plant growth and variation (Prusinkiewicz and Lindenmeyer 1990). More recently, several volumes mark significant increases in application of this knowledge. "The Nature of Code" provides a framework for software simulation of natural forces such as gravity, friction, and velocity, enabling the designer to visually program these elements and understand how they act upon a 3D field using "processing" (Shiffman 2012). "Generative Art," a book on creative workflows, covers methods of visualizing fractals, growth, and emergent properties of groups of organisms (Pearson 2011). And in "Dynamic Patterns: Visualizing Landscapes in a Digital Age," several digital projects explore these phenomena through generative computational design approaches to the field of landscape architecture, with an environmental site-based approach to emergence, patterns, interaction, and feedback (M'Closkey and VanDerSys 2017).

Advances in 3D simulation have focused on simulating the flow of water on terrain. Work in digitally simulating riverine flows has produced valuable ideas regarding robotically controlled computation infrastructure to manage sedimentation (Cantrell and Yates 2015). Other research uses engineering software to simulate riverine water flow using geospatial analysis, computational fluid dynamics, and parametric software, providing output that has expanded the designer's ability to guide natural processes that are difficult to detect through immediate observation (M'Closkey and VanDerSys 2017). Austin Becker and Peter Stempel of the University of Rhode Island, in collaboration with the Coastal Resources Management Council, have digitally modeled storm surges and erosion to create visualizations of potential housing damage that future storm events may cause.

The Need for the Project

Each of these projects addresses a specific aspect of simulating natural systems within the built environment, yet landscape architects still need a tailored workflow to augment the overall design process. The goal of this project is to create a workflow that enables landscape architects to simulate future conditions of a site and create a responsive design proposal. Moving beyond simple strategies for visualizing sea level rise such as the "bathtub method" (raising the water plane to a prescribed inundation level), this research collectively visualizes erosion, sea level rise, and inundation as a result of storm surge. By using a range of geospatial, image editing, 3D modeling, and animation tools, the researchers were able to successfully model a hypothetical coastal storm event using numerous factors that had previously not been considered. The result is a reusable workflow that affords the designer a holistic appreciation of the impact of changing natural systems on design for coastal areas.

PROJECT OVERVIEW

This project aimed to simulate characteristics of the natural environment in order to understand design application within natural processes. A core goal of the project was to develop a digital workflow that was flexible enough that it could be applied to a broad range of coastal sites and conditions. Designing such a workflow required initial research to understand the range of software programs used by design professionals. Given that the project's aim was to create a workflow for landscape architects, architects, and urban designers, the team felt that the project's simulations should be created with tools most commonly used within the spatial design professions.

The methodology created through this research is intended to accomplish two goals. The first is to provide a realistic animated simulation of coastal ecological conditions. The second is to evoke a visceral emotional reaction in the viewer, as such reactions may enable the designer to more deeply understand coastal complexities, to visualize the irregularity and spectrum of natural forces, and to foment design inspiration. Through this methodology, we sought to add 3-D depth to systems that are often displayed two dimensionally. This depth allows ecological systems to make use of a familiar visual language—that of the 3-D world—that is routinely utilized for understanding spatial relationships.

The methodology was designed to align with scientific principles and research on the topics of sea level rise, erosion rates, and storm surge conditions. However, this methodology should not be interpreted as a system that can predict or forecast with exactitude how these coastal systems will evolve under acute and long-term climatic stresses. The complexity of these systems, the translation of their principles into a workflow more familiar for designers, and the process of working in multiple software programs all contribute to some loss of precision. Instead of a predictive modeling tool, this methodology should be seen as an addition to growing endeavors in visualizing natural systems for design applications. Digital and physical modeling are integral to how designers perceive environments, test design strategies, and understand spatial representations. Our introduction of a new technique for modeling coastal erosion and hydrologic systems should be seen as adding to this modeling discourse by leveraging advances in computational power and efficiency to create relatively quick, iterative models of complex phenomena.

Assumptions

The team made some key assumptions in order to make the methodology more accessible and streamlined. These assumptions allowed us to focus on developing certain key aspects of the workflow. We believe that these assumptions do not hinder the integrity of the process and the final outcomes despite the uncertainty of so many future factors that could alter outcomes such as sea level rise, storm frequency, ocean warming, and coastal development trends. Regardless, in future phases of the project, some of these assumptions may be revisited and explored further in an effort to offer increased accuracy.

The first major assumption was that erosion rates would remain constant throughout the timeframe explored. Though it is known that erosion rates change frequently, to simplify the process an erosion rate spectrum was created by using a low erosion rate of 0.25 m/yr and a high erosion rate of 0.5 m/yr (which is greater than the average recorded rate in that area since 1939) (Boothroyd et al. 2015). These rates were selected to account for the variation of erosion rates throughout 50- and 100-year time frames. The erosion rates were also selected because of the uncertainty about sea level rise rates over the next 100 years. Rising seas are predicted to increase erosion rates due to a wave's ability to erode higher elevated materials and to maintain its force before breaking because of a lower seabed. Given these variables and the uncertainty of how they will play out in the real world, the team defined a single fixed erosion rate for the project.

The second assumption was that the material composition of the coastline would remain fixed with no further armoring or nourishment. Though existing armoring in the study area suggests that further construction could occur, the team felt that there was too much uncertainty about when and how it would take place. There was, for example, uncertainly about which armoring methods might be applied, when such armoring might be undertaken, and overall future development trends in the area. Coastal nourishment programs that restore naturally eroded coastline are undertaken either to mitigate chronic erosion or in response to a severe storm. Because of the high cost of nourishment programs and the uncertainty of severe storm systems, the presence of coastal nourishment programs was not considered as part of this project. However, it is possible to account for planned nourishment with the current methodology.

The accuracy of the project's methodology is to some degree limited by these assumptions. Because of this, the methodology should not be used to highlight individual real estate at risk of inundation or foundation erosion. The methodology also does not demonstrate how wind would impact the ways that water would disperse on land during storm events, and therefore it should not be used to describe the full extent that water could navigate throughout a site. Rather, it should be used for making broad inferences and discoveries about coastal ecological systems and their impacts on design sites.

METHODS

The modeling of coastal erosion, sea level rise, and storm surges to create future scenarios first required gathering a current topographical model that could be the base for further augmentation. We acquired a digital elevation model (DEM) from the U.S. Geological Survey's (USGS) National Map Viewer. The DEM of Misquamicut, Rhode Island, was imported into in ESRI's ArcMap GIS software. Using orthoimagery provided by ESRI's online database, we determined site extents and trimmed the DEM to the extent of the study area.

To create erosion scenarios for future conditions, we researched past erosion rates for the site. We examined the Rhode Island Geographic Society's historic erosion rates since 1939. From those rates, we created high and low erosion scenarios. We decided on a low erosion rate of 0.25 m/yr and a high rate of 0.5 m/yr because they represented the two extremes experienced on the site. Though 0.25 m/yr was not the lowest erosion rate in the historic data, we selected it because of the effects of climate change. We assumed that future erosion will accelerate beyond past rates as a result of higher sea levels and increased storm severity. The high erosion rate scenario of 0.5 m/yr is conservative for the same reasons. We used these erosion rates to create 50- and 100-year scenarios for both the high and low erosion rates (Fig. 1).

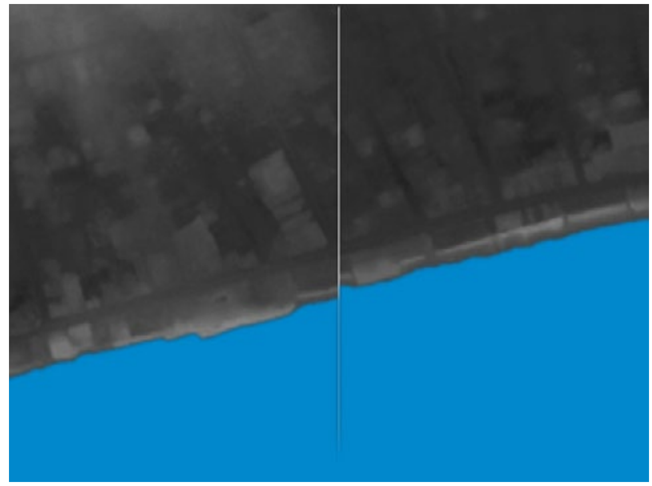

Figure 1.—Original DEM (left) and low erosion rate +50 yr scenario (right).

We then imported the DEM of Misquamicut, Rhode Island, into Adobe Photoshop using a plugin named Geographic Imager. This tool allowed us to "translate" the coastline of the DEM in response to the distance determined by the erosion rates and the timeline. We accomplished this translation using Photoshop's clone stamp and its measure tool, which allowed a fixed distance to be maintained as the coastline was modified. Using these tools, the coastline of the DEM was retreated to create basic erosion scenarios (Fig. 2).

We exported these modified DEMs from Geographic Imager and imported them into Rhinoterrain, a plugin for McNeel's 3D modeling tool Rhinoceros (Rhino). Rhinoterrain turned the imported DEMs into 3D models of the topography. We created a flat plane, which represented a simplified measurement of sea level height, at 2 ft, 4 ft, and 6 ft above current mean tide where it intersected with the terrain model. However, this method was limited in value. It would only show flooded areas that were of the same elevation as the plane and it was not able to account for a dynamic ocean that would more deeply inundate certain areas because of wave action and wind. To create a more realistic model, we needed to create an animated simulation of waves and water flow.

To create this simulation, we decided to integrate Autodesk's 3D animation modeling program Maya and its water modeling simulator Bifrost. Maya and Bifrost are more frequently used by the animation industry than by the building industry but they have value as modeling tools because they can create hydrological

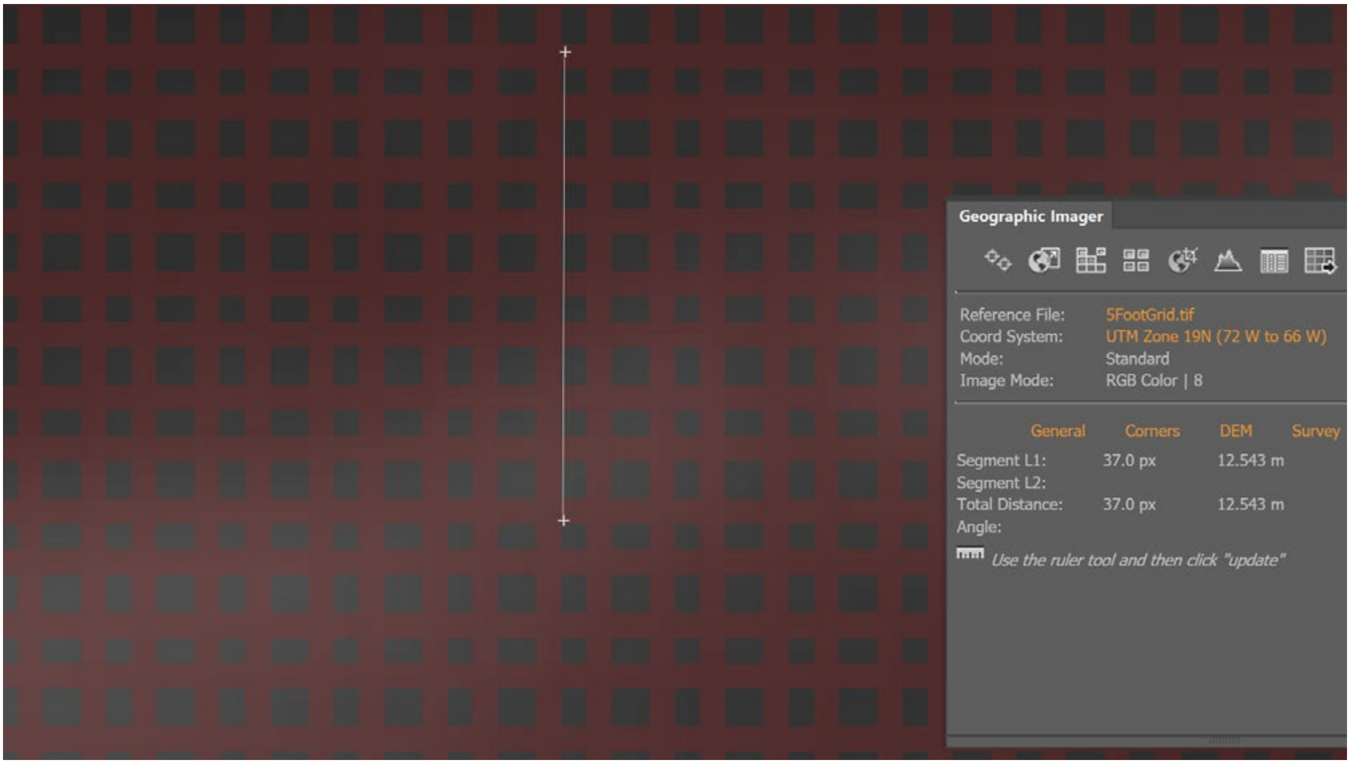

Figure 2.—Grid layout using Geographic Imager in Adobe® Photoshop® showing distance measurement overlaid onto modified DEM.

simulations that use physics-based fluid computations. This is done through Bifrost's fluid implicit particle solver for creating animations of various fluid types and scales. We understood the potential of these tools to create a large-scale body of water that could behave like an ocean, enabling us to generate more realistic storms systems and sea level rise scenarios.

To create this digital water body, we chose a storm surge scenario. The first step in modeling this scenario was to understand the potential height of such a storm surge. For this, we used the Sea, Lake, and Overland Surges (SLOSH) model from NOAA's hurricane modeling system to provide storm surge ranges for the site's general vicinity. We used a category 1 hurricane to estimate the height of a storm surge. We chose a category 1 hurricane because of its higher probability of occurrence. Because of this methodology's flexibility, it can be amended to accommodate any storm surge scenario.

Because of the computational power required to produce the animations, we divided the site into smaller sections. We exported each section from Rhino and imported it into Maya. We created a polygon to fill a basin representing the site's bathymetry and scaled it to touch a plane that represented the height of an 11 ft storm surge; the SLOSH program determined that this height was possible. We transformed the polygon into the Bifrost liquid that would interact with a geometry that would create a force to propel the water toward the beach in a fashion similar to stormy waves (Fig. 3). We used deformers to modify the geometry to create regular, semi-unique wave forms of customizable heights, shapes, and frequencies that would roll in a prescribed direction over time. We could increase or decrease their influence to modify their effect on the fluid.

To create the kind of periodic irregularity that would occur in swirling winds and turbulent waters, we added a paddle to the rear of the basin to create occasional fluctuations in the storm surge's height. We animated the paddle to oscillate along the x-axis at a speed that matched the waves. We programmed an expression into the paddle's amplitude to add a cross wave as it oscillated. This helped to create a more dynamic effect within the ocean waves (Fig. 4).

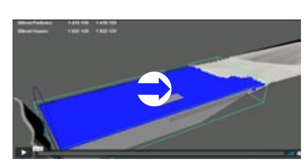

Figure 4.—Video of Accelerator + paddle with 11ft. storm surge (click to play video).

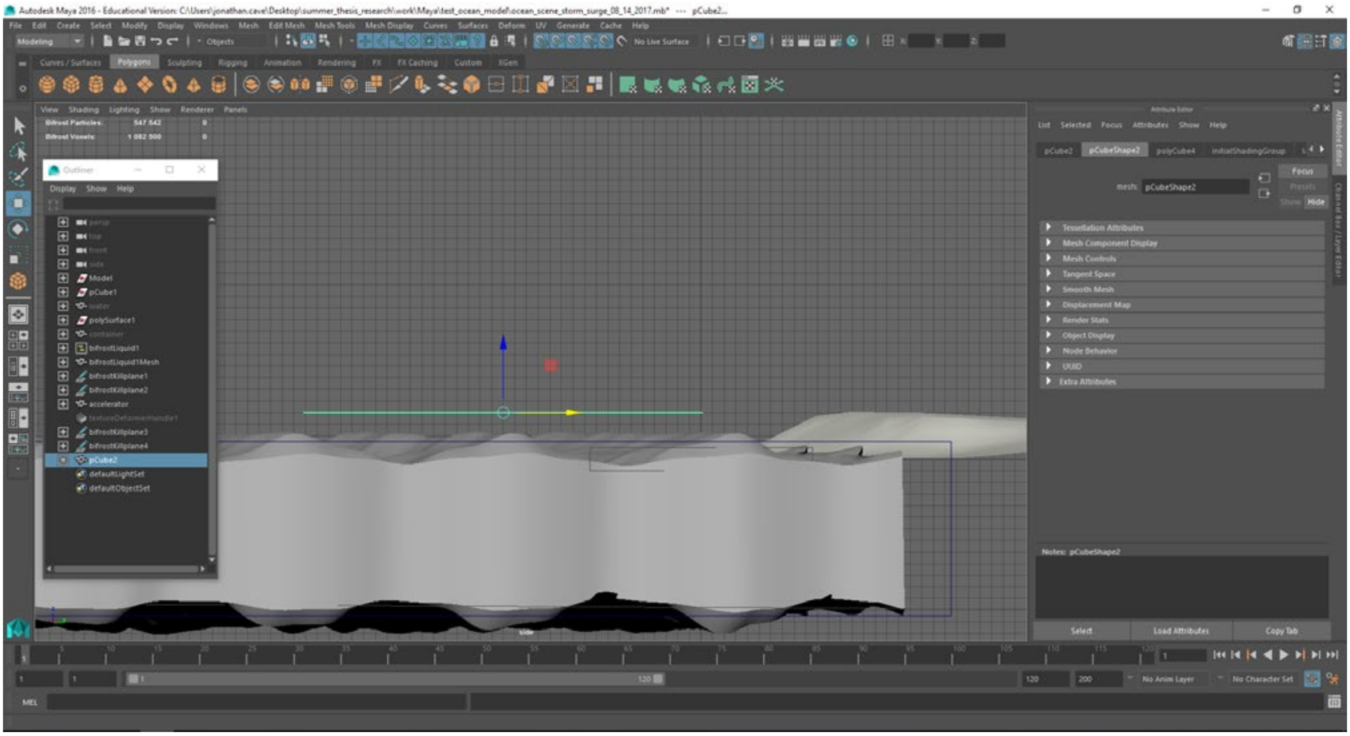

Figure 3.—Accelerator with 11 ft storm surge.

Figure 5.—Video of storm wave in Maya showing current conditions with storm surge (click to play video).

We ran a series of playblasts—short, screenshot videos—to develop draft videos before creating the animation and a mesh. We exported this animation to create the first movie depicting a storm surge on Misquamicut's current coastline condition (Fig. 5). To observe the impact of erosion on a storm surge, we imported the erosion terrain models to replace the existing terrain model. This enabled many possibilities: We could rerun the animation to visualize the difference between the two conditions under the same storm surge or modify the process to depict a higher mean tide to simulate sea level rise or a more forceful storm surge to depict a stronger hurricane or Nor'easter (Fig. 6).

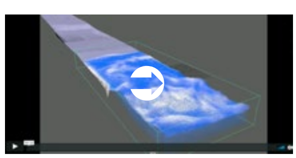

Figure 6.—Video of storm wave in Maya showing 6ft. of sea level rise + 25m/yr. erosion rate (click to play video).

FINDINGS

The use of Bifrost in conjunction with our topographic models began to demonstrate how the ocean could interact with coastal conditions at varying degrees of intensity. Once we simulated a storm surge, we could see water breaching coastal barriers, posing a risk to infrastructure, settlements, and vulnerable ecologies. The simulations were able to demonstrate how both human and natural ecologies might become more vulnerable to periodic, semi-regular, and chronic inundation. Further development of this simulation model would add structures and natural systems that would further interact with the water as it breached the natural and human barriers. For our site, this would entail adding Winnapaug Pond, Little Maschaug Pond, and the buildings that occupy the coastline.

This methodology helped us to create quick representative models of coastal change and process that improved our understanding of the coastal systems' complexities and irregularities. On a personal level, we discovered that the process of creating these animations was as meaningful and informative as viewing the final animation. Creating physical iterative models of coastal systems can be challenging because of the difficulties of generating accurate fluid simulations, especially at scale. Yet the process of modeling is an essential explorative method in analysis and design formation, a "tool people use to organize their mental perceptions of perceptible, phenomenal reality" (Centofanti et al. 2014). Through engaging in this process of digital modeling, the dynamism of the coastline becomes more observable and intellectually and emotionally understood.

The final animation that we created highlighted the strength of this new methodology as an iterative process. Because we modeled the fluid simulator independently of the coastal topography, we could change locations and scenes or augment the landscape to see how these changes would influence the interactions between the various modeled factors.

DISCUSSION

While it relied heavily on scientific data, this process contained significant trial and error. This was due to the continual translation of scientific principles that dictate natural systems for software workflows. Especially in the later stages of the project when animations were generated, results were often unexpected and surprising. To verify accuracy, the team would watch videos of coastal storm events to understand whether the exported products of our methodology shared similar properties with real-life events. Although the final animations match the visual behavior of similar water bodies, some technical discrepancies can be expected. The team believes that with the consultation of an oceanographer and a digital artist who is an expert in Maya and Bifrost, a more precise model could be created.

Through this process, we understood that there was potential to add error when retreating a coastline within Geographic Imager and Photoshop. However, because there is inevitable flux in actual erosion rates over time, we did not consider the minor distance variation a drawback to the methodology.

Although the first iteration of this workflow is complete, the team has been unable to test it at the full site scale due to the unavailability of a computer that offers sufficient computational power. While we do not believe a large scale will alter our core methodology, we cannot say for certain what effect it would have. For now, we are using representative sections of various topographies across the study site.

These challenges in the methodology do not diminish the applicability of this modeling approach but rather invite even greater collaboration. Currently, scientists use many modeling methods to explain natural systems that design professionals do not use. It is our belief that, while it is important that these methods are integrated into the design process, these models are most effective when initiated by the scientific community. We are excited about this methodology's potential to work with tools that are geared toward designers but have input and direction from the scientific community. We believe this process opens a dialogue between the parties to exchange information and methodologies that are more familiar to each discipline, with the aim of further understanding both the natural system and modeling processes.

On a conceptual level, the ability to view these dynamic natural systems in action elicited a sense of wonder, awe, and even fear in the team. This may signify the potential to augment the designer's mental approach to the tasks and provoke a more fundamental appreciation of the dynamic systems within which they plan to intervene. These systems, which are typically represented in landscape architecture as static images in plane and section, can be seen as time-based phenomena acting upon the design site. The ability to view water moving into a site repeatedly and to consider this scenario playing out over weeks, months, and years may lend the designer a deeper sense of the impact or nonimpact that their design could have.

It is our hope that a methodology like this can further the dialogue between disciplines to create more visual languages and new perspectives on ecological conditions. This methodology builds off others that are being introduced into the design professions and it is our hope that others will adapt these principles in new ways to improve our analysis and understanding of ecology and inspire new approaches to landscape design.

CONCLUSION

Adding this methodology to the existing set of computational 3D modeling workflows will help scientists and landscape designers understand the challenges of climate change in the 21st century and beyond. These kinds of techniques have the power to help designers, developers, and politicians make informed decisions about coastal settlements and natural ecologies. It is our hope that such tools will enable effective decision making that can preserve the visual, cultural, and ecological functionality of our coastlines in the midst of great climate change and uncertainty.

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