Computation and Visualization of Coastal Sea Level Rise Mitigation Strategies: Digital Applications of Scientific Data to Formulate Design Workflows for Climate Change

Aidan Ackerman[1], Jonathan Cave[2], Kyle Stillwell[3]

[1]SUNY College of Environmental Science and Forestry, Syracuse/USA · acackerm@esf.edu
[2]Boston Architectural College, Boston/USA
[3]SUNY College of Environmental Science and Forestry, Syracuse/USA

Abstract: This research investigates a digital workflow for simulating and visualizing the impact of extreme storms on the coastal landscape, and for testing the effectiveness of landscape designs intended to mitigate the sustained damage caused by these storms. We discuss the methods used to visualize increasing sea level heights and shoreline erosion using two and three-dimensional digital modelling software, and the methods used to create animated simulations of wave behaviour during coastal storms based on historic storm data. This paper also includes the creation of a digital landscape design which aims to mitigate the impacts of sea level rise, erosion, and storm surge in a simulated environment, visualizing the potential for restoration of lost ecologies through relocation of coastal water bodies to an inland area. The results show that the use of digital tools can uncover critical impacts of climate change on the coastal landscape, providing a useful framework for testing design mitigation of these problems.

Keywords: Simulation, climate change, sea level rise, erosion, waveform

1 Introduction

Landscape architects are increasingly in need of digital tools to model and visualize long-term environmental flux because of climate change. They face challenges of ever greater complexity as anticipating climate change impacts becomes standard practice in the planning, design, and engineering professions. These challenges include rising population density in coastal areas, coupled with an imperative to design resilient landscapes which can handle extreme weather events (MELSOM et al. 2015). Landscape architecture software workflows are pressured by the demand to use sophisticated digital tools in addressing complex climate change scenarios (SALGUEIRO et al. 2015). These pressures require adaptation of traditional design processes to create aspirational designs which can endure extreme weather events (DOYLE et al. 2015). Landscape architects are the ideal creators of digital tools for visualization of climate change, as they are equipped with the analytical, communication, and collaboration skills to move society towards climate action (SHEPPARD 2015).

In the coming decades, coastal areas will be exposed to high risk of sea level rise and erosion, resulting from anticipated climate-related changes. These changes include: accelerated sea level rise of up to 0.6 meters by the year 2100; increase of sea surface temperature up to 3°C; and larger ocean waves and storm surges (NICHOLS et al. 2007). For coastal zone managers and municipal planners to act quickly in the face of these oncoming threats, they need an objective, quantitative assessment which shows the risk to structures, infrastructure, and public safety caused by sea level rise and coastal erosion – such as the Coastal Environmental

Journal of Digital Landscape Architecture, 4-2019, pp. 10-20.
Berlin · Offenbach. ISBN 978-3-87907-663-5, ISSN 2367-4253, e-ISSN 2511-624X, doi:10.14627/537663002.

Risk Index (CERI), developed to enable decision making in the face of coastal climate change (SPAULDING et al. 2016). Although advances in GIS-based visualization have intensified in recent years, further improvements are needed to enable accurate impact assessment methodologies, the development of design guidelines, and the representation of climate uncertainty. Such improvements are necessary for climate change modelling visualizations to be used as a decision-making tool (DOCKERTY et al. 2005).

The dilemma of modelling large-scale systems for future unknowns, and the losses which may occur due to errors in predictive modelling, are formidable. We are unable to perfectly model future rates of sea level rise based on current information: the underlying risks of sea level rise, already noticeable, may be significantly different in the future than they are today (BROWN et al. 2005). This adaptation necessitates technology which can respond quickly to complex parameters, incorporate them into every stage of the landscape architecture design process, and illustrate their potential outcomes in visually meaningful ways which can be interpreted by the public (BROWN et al. 2005). When considering the large number of variables and algorithms necessary to visually describe the behavior of coastal ecological systems, a single software application geared towards landscape architects is unlikely to capture this level of complexity. Therefore, we propose workflows which use multiple digital tools to address these challenges and respond with design alternatives informed by scientific data.

2 Methods

2.1 Modelling Sea Level Rise and Storm Surge

This research collectively visualizes erosion, sea level rise, and storm surge, achieved using geospatial, image editing, 3D modelling, and animation tools. Combining these tools in new ways, we were able to model these climate-related forces as a set of dynamic, fluctuating relationships. To create erosion scenarios for future conditions, we researched past erosion rates for the site – a densely populated barrier beach in coastal Rhode Island – and used these rates to create 50- and 100-year scenarios. These scenarios included simulations for both 0.25m/yr and 0.5m/yr, both of which are greater than the average recorded rate in that area since 1939. 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. Two erosion rates were selected because of the uncertainty about sea level rise rates over the next 100 years. Once these erosion rates were determined, we acquired a DEM from ArcMap, and then computationally eroded the coastline at these set rates. To accomplish this digital erosion, we imported the DEM into Photoshop using a plugin named Geographic Imager. This plugin allowed the spatial properties of the image to be automatically updated and retained throughout the raster image editing process, allowing us to 'translate' the coastline of the DEM using Photoshop's clone stamp to sample and paint coastline pixel data further away from the coastline, while using measurement tools to retain accurate distances (Figure 1).

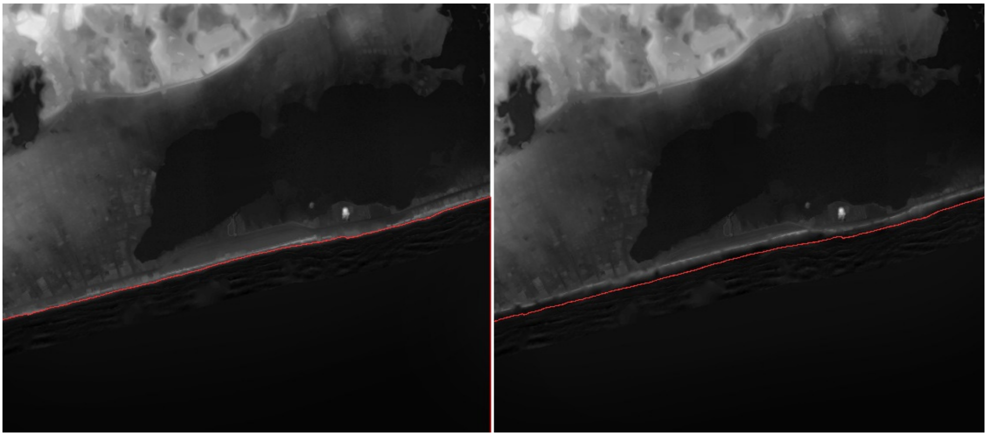

Fig. 1: Original DEM (left) and low erosion rate + 50yr scenario (right)

After creating several modified DEMs representing various erosion scenarios, we converted them to Rhino terrain meshes. We then created a flat plane representing a simplified measurement of sea level height, at 2ft, 4ft, and 6ft above current mean tide. We coupled the eroded terrain models with corresponding sea level heights, enabling us to see the combined effects of sea level rise and its impact on shoreline erosion. The visualizations of these increasing sea level heights, in combination with the eroded coastlines of the exported terrain models, show dramatic changes in the coastline. Compared to visualizations which only show sea level rise, these visualizations indicate greater levels of potential inundation, effectively demonstrating that barrier islands would quickly give way to ocean inundation into freshwater ponds, located just inland off the shoreline (Figure 2).

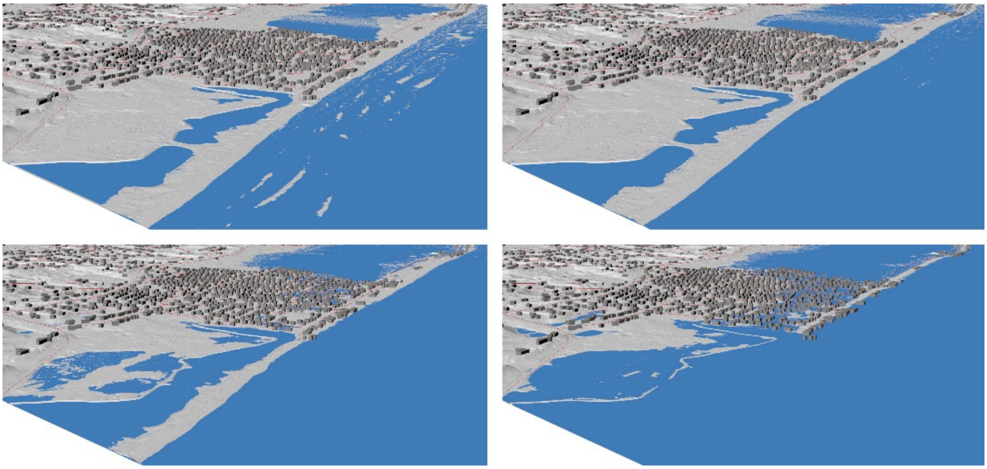

Fig. 2: 3D model with 0.25m/yr and 0.5m/yr erosion and 2ft, 4ft, and 6ft sea level rise

To visualize the ocean as a living, fluctuating system, we created an animated simulation of waves and water flow. This enabled us to more realistically visualize a dynamic ocean which would more deeply inundate certain areas because of wave action and wind. We referenced the Sea, Lake, and Overland Surges (SLOSH) model from NOAA's Hurricane Modelling System to provide storm surge ranges for the site's general vicinity, and selected data representing a category 1 hurricane, which has the highest probability of actual occurrence (JELESNIANSKI et al. 1992). SLOSH models are organized into 38 elliptical basins, with each basin containing multiple grid cells. Multiple simulations are performed for each grid cell, performing hurricane simulations which utilize a range of forward speeds, landfall directions, and landfall locations to report the maximum surge height for each basin. When applied to large areas of land, SLOSH models are considered to be 80% accurate, and therefore represent a generalized condition with some inherent misrepresentation of local conditions (FRAZIER et al. 2010).

To visualize the movement of fluid particles in three-dimensional space over time, we imported the modified Rhino terrain model into Maya. Maya includes a tool called Bifrost, a procedural framework which includes an Ocean Simulation System, which can create realistic ocean surfaces with waves, ripples, and wakes (ZASPEL et al. 2011). Bifrost relies upon a fluid implicit solver for the Navier-Stokes equations to simulate fluid motion, written here in pressure-velocity variables:

$$\nabla \cdot u = 0$$

$$\left(\frac{\partial}{\partial t} + u \cdot \nabla - v\nabla 2\right) u = g - \frac{1}{\rho} \nabla p + f$$

where $\nabla = (\partial/\partial x, \partial/\partial y, \partial/\partial z)$ is the gradient operator in 3-D,
$(\partial/\partial t + u \cdot \nabla - v\ \nabla 2)$ is the frequently-recurring convection-diffusion operator, and
f is an external force per unit mass.

To simplify the simulation, we focused on a small topographic slice of the site where we had modelled significant erosion of a barrier island. This simplification was necessitated by the complexity of the digital terrain and water movement, which required significant computing power to model even a small study area. We then 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 11ft storm surge, which was the maximum possible height determined by the SLOSH model. We transformed this polygon into a Bifrost liquid that could be propelled towards the beach with those properties found in waves created by a storm event. To create the rhythmic variation seen in ocean surfaces, we used deformers which could modify the geometry to create regular, semi-unique wave forms of customizable heights, shapes, and frequencies. We also modelled a flat plane, similar to a paddle, to the rear of the basin to create occasional fluctuations in the storm surge's height. These periodic fluctuations enabled slight randomness, accounting for unexpected inputs to the wave movement. Lastly, we programmed an expression to add a cross wave, which added to the general realism of the wave motion. Once this was complete, we ran a series of animations of this fluid model in combination with the terrain, observing that the tiny remnant of the coastal barrier island could be easily breached by storm surge, removing any remaining protection to the heavily populated inland area (Figure 3). Moreover, this complete loss of the barrier island, and the influx of coastal waters, could dramatically alter the composition of the adjacent ecosystem. Most notably, we observed that the advanced level of shoreline retreat could significantly reduce or eliminate areas of inland swamp, as well as brackish and freshwater marshes, which are some of the most biodiverse areas of coastal ecosystems (LEVIN et al. 2001).

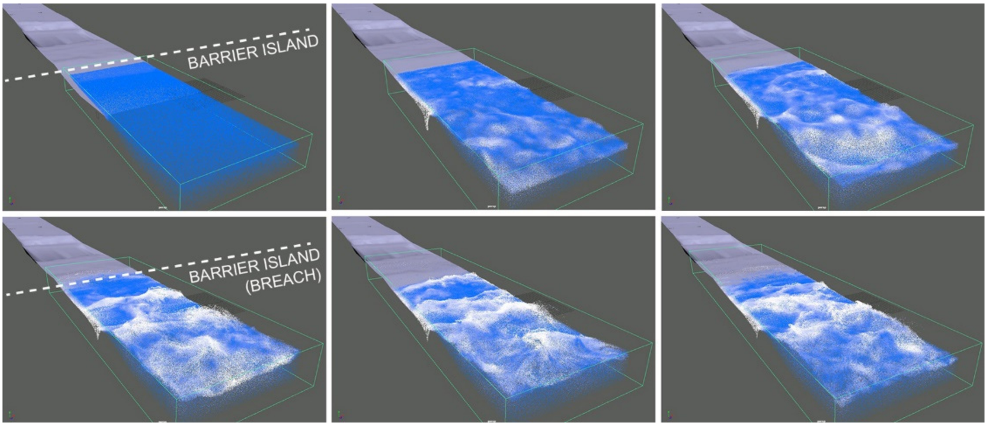

Fig. 3: Initial animation test of erosion condition using wave simulation

2.2 Modelling a Landscape Architecture Mitigation Strategy

Once the interrelated impacts of sea level rise, erosion, and coastal storms had been visualized, we began creating an adaptive design response which would serve to restore or recreate those ecologies which our models indicate would be reduced or lost. Using data from remote sensing aerial imagery, combined with land typology GIS data, we mapped specific ecological areas onto our simulations. These indicate that the advanced level of shoreline retreat could significantly reduce or eliminate areas of inland swamp, as well as brackish and freshwater marshes. With these losses in mind, we set out to develop a design strategy which would preserve these reduced ecologies through gradual inland relocation. This is an uncommon tactic, as many sea level rise design interventions aim to mitigate damage in situ using barriers to keep water out or inlets to allow water to circulate around infrastructure and property. However, there are advocates for “horizontal” coastal landscape design strategies, using living systems to absorb wave energy and water (HILL 2007). In contrast, the design strategy emerging from our research prioritizes the full relocation of major ecological areas, while aiming to have a minimal impact on existing built form. Within the study area, our research indicated that the largest inland water body facing total loss was a swamp and salt marsh fed by a saltwater estuary connecting to the ocean (Figure 4). Our models indicated that sea level rise and erosion would eventually convert this water body to coastal beach, a change made even more dramatic due to loss of barrier islands. In *Design for Flooding: Architecture, Landscape, and Urban Design for Resilience to Climate Change,* Donald Watson specifies measures to be taken in creating resilient design for inland flooding. The goals of an integrated approach to watershed protection include: reducing flooding during extreme events, providing healthy water for humans and nature, and restoring impaired waters such as the inland water bodies that appear to be threatened in our simulations (WATSON 2010). With these goals in mind, we asked the radical question: could a landscape design possibly recreate this lost coastal ecology through restoring it in an inland location?

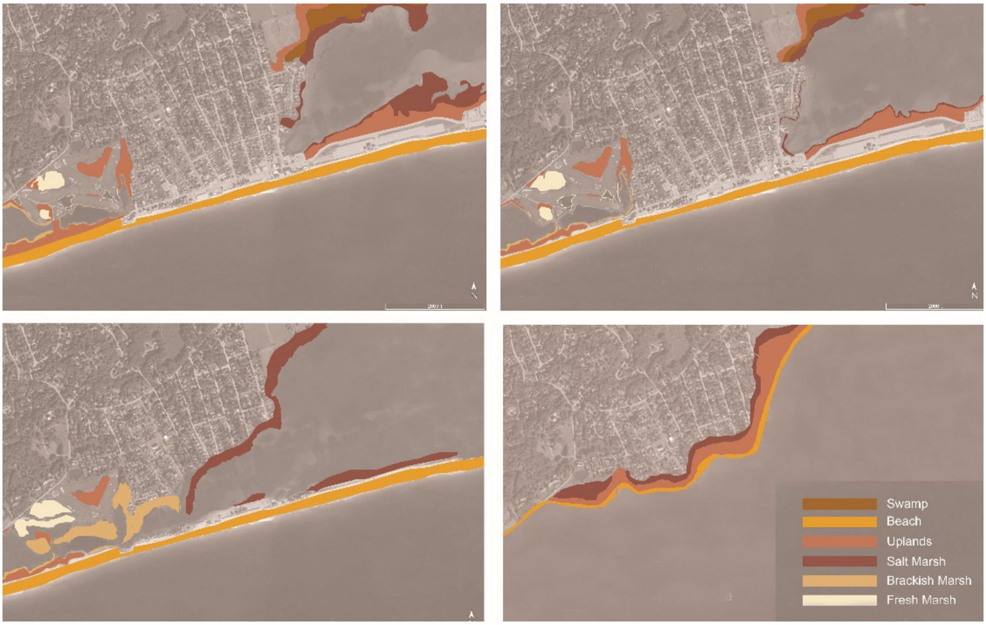

Fig. 4: Predicted loss of ecological areas along the coastline, with inland water body loss

The first step was to identify a suitable area to relocate the coastal swamp and salt marsh. Inland site selection relied upon finding an area that was relatively undisturbed by development, low-lying and large enough in area to accommodate a significant water volume. These criteria led us to select an area of inland mixed forest and swamp adjacent to the municipal airport. Although significant further analysis would be necessary to determine real-life site suitability, this level of analysis can be considered an initial framework upon which to explore a conceptual design strategy. The next step was to identify a basin which would gradually be inundated as water levels rose, fed by connecting channels. The first identified basin was located a few hundred feet from the closest area of predicted inundation from sea level rise, separated from the inundation area by a single road. We re-graded the edge of the basin, proposing a bridge over the connective inlet. This grading effectively connected the inland basin to the Atlantic Ocean, somewhat recreating the lost brackish marsh condition observed in the earlier simulations.

For this basin to effectively channel coastal water inland, it would need to be broken up into a series of smaller tidal channels. This would serve two purposes: to mimic the estuarine morphology which allows water to flow naturally inland from the ocean, and to serve as a naturalized barrier during a major storm event, when storm surges rush into low lying areas at high speed, resulting in amplified shoreline erosion and increased flooding. Acknowledging that coastal landforms are healthiest when they can shift and be shaped by the flows of wind and water, we modelled geometric landforms which could accept the flowlines of estuarine meanders. The Renaturalization of the River L'Aire in Geneva, Switzerland is an example of this type of strategy, where a series of lozenge forms were constructed in an existing riverbed channel (Figure 5). Over the course of a year, the natural flow of water through the lozenges reshaped them into a more naturalized form. This type of strategy can be seen less as a final design, and more of a constructed point of departure for the natural systems to design themselves. Given that our simulations were speculative, they indicate not a single outcome, but rather a range of possibilities. As such, we were drawn to a mitigation strategy which could adapt to a range of outcomes, serving as a datum for perpetuating naturalized conditions without demand for absolute predictive accuracy.

Fig. 5: Superpositions: Renaturalization of River L'Aire. Images reproduced with permission, photo credit: Easytomap.

Drawing inspiration from the River L'Aire project, we applied a similar lozenge form in the new water inlet, at a height of 6 feet from the basin floor, and a single edge length of 32 feet. These dimensions were drawn from the River L'Aire project's earthwork. The positioning of this lozenge pattern transitioned from a coastal edge, through a narrow inlet, to the mouth of the inland basin. This positioning was intended to support the naturalized flow of coastal water through the lozenge pattern, allowing the water to evolve into a naturalized estuarine morphology through interplay with the constructed landforms (Figure 6).

To visualize how the natural flow of estuarine water might soften and naturalize this linear geometric array, we then used Geographic Imager to render various iterations of the geometry upon a DEM exported from Rhino using the ShowZBuffer tool. In Photoshop, we used brushes and erasers to amplify certain flow paths and suppress others, measuring and dimensioning our brush strokes to accurately constraint to the meanders of an estuary. The result is a series of snapshots of what naturalized conditions might emerge over time within our design. Using the same methodology as was applied previously to visualize storm surges along the coastline, we ran versions of the new model through our previous Bifrost particle simulator to visualize the possible force of a coastal storm on this reshaped landscape. The resulting animation allowed us to better comprehend the scale and structure of the lozenge landforms and the ways that they could interact with waves (Figure 7). We observed that the velocity of the water particles decreased slightly when encountering the lozenge forms, indicating an ability of the earthwork to mitigate erosion caused by fast-moving storm waves. However, it was unclear whether this ability would remain a long-term benefit of the design, given that eventual softening of the lozenges would occur.

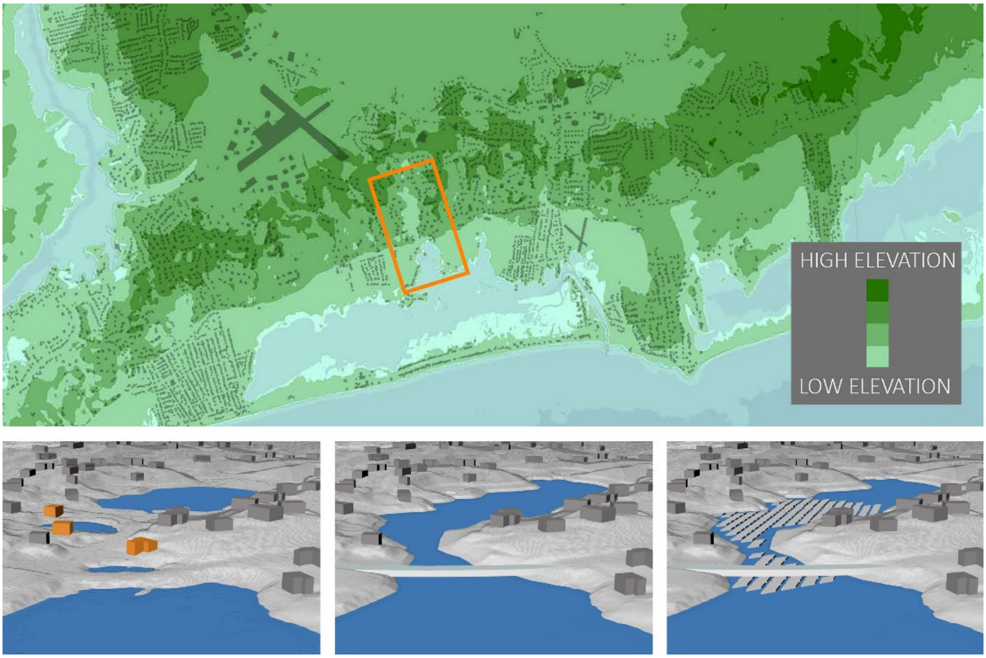

Fig. 6: Proposed earthwork to allow mixing of fresh and salt water. Tidal marsh shown with .05m/yr erosion + 6ft sea level rise. Orange buildings to be removed for regrading.

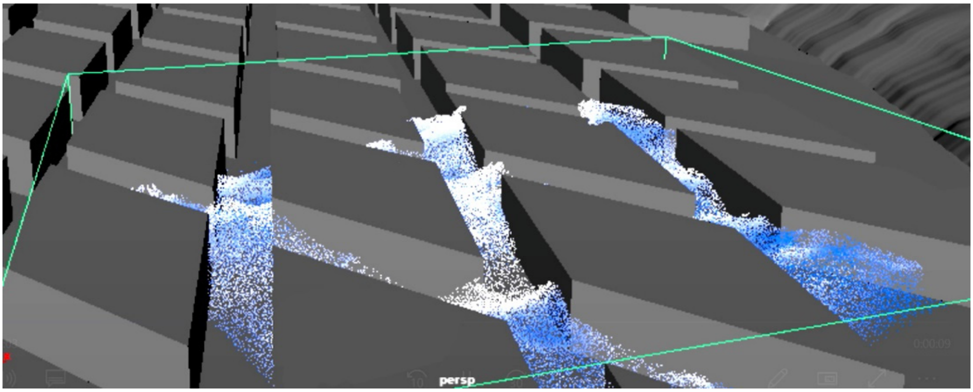

Fig. 7: Eye-level view of the design prototype with wave simulation

3 Findings

The use of digital tools to erode coastal terrain based on scientific data offers a powerful approach to visualizing sea level rise in combination with coastal erosion. We found that this workflow alone increased our knowledge of the limitations of landscape architecture to hold rising coastal waters at bay, and we were encouraged to explore alternative design paths. The added simulation of coastal storms began to demonstrate how the ocean could interact with coastal conditions at varying degrees of intensity, and engendered appreciation for the hydrologic forces landscape architects contend with in designing coastal projects. 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. This important finding was the catalyst that caused us to seek a design alternative which would dramatically alter the path of coastal and inland waters to recreate lost biodiversity through the creation of inland basins. This methodology helped us create quick representative models of coastal change and processes that improved our understanding of the coastal systems' complexities and irregularities, as well as the potential for landscape architecture to interrupt serious coastal damage from sea level rise and erosion. The integration of various models has enabled us to re-run animations to visualize the difference between two erosion states during the same storm event, highlighting the strength of this new methodology as an iterative process.

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 into software workflows. Especially in the later stages of the project when animations were generated, results were often unexpected and surprising. The most significant shortcoming of this research was the limited physical area that could be included in animated simulations. Although we were able to successfully model partial sites and small-scale earthwork, the larger impacts of these design strategies on coastal water flows were beyond the available computational power. Given that these natural systems have causes and effects at a range of scales, from immediate to global, the absence of any large-scale animated simulation is problematic. Although we can rely on 2D raster image editing to explore erosion for now, in future stages of this project it will be imperative to enable animated computational simulation of larger natural forces. The limited accuracy of SLOSH models at the local scale further compounds the need to scale up the animation footprint to enable visualization at a larger scale.

4 Conclusion

The ability to view these dynamic natural systems in action elicited a sense of wonder, awe, and even fear in the research 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 plan 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 non-impact that their design could have.

Digitally “testing” designs within the same digital workflows used for analysis allows us to understand their effectiveness under the same conditions which inspired their creation. This allows us to move beyond analysis alone, and into understanding the agency of landscape architecture in mitigating the threat of climate change. The information that this research yields about the possibility of channelling water inland from an ocean area is limited in that it offers primarily visual information, and requires in-depth further study using fluid mechanics and water resources engineering calculations in order to enter a realm of feasibility. However, this research offers an initial approach to large-scale landscape adaptation built upon scientific data, enabling the designer to understand the nuances of coastal landscape systems through simulations which consider sea level rise in combination with erosion and storm surge. We hope that these digital workflows will enable resilient and sustainable landscape architecture design processes which will preserve the visual, cultural, and ecological functionality of our coastlines in a time of climate change.

References

BROWN, I., JUDE, S., KOUKOULAS, S., NICHOLLS, R., DICKSON, M. & WALKDEN, M. (2006), Dynamic Simulation and Visualisation of Coastal Erosion. Computers, Environment and Urban Systems, 30, 840-860. https://doi.org/10.1016/j.compenvurbsys.2005.08.002.

DOCKERTY, T., LOVETT, A., SÜNNENBERG, G., APPLETON, K. & PARRY, M. (2005), Visualising the Potential Impacts of Climate Change on Rural Landscapes. Computers, Environment and Urban Systems, 29 (3), 297-320. https://doi.org/10.1016/j.compenvurbsys.2004.05.004.

DOYLE T., CHIVOIU B. & ENWRIGHT N. (2015), Sea-Level Rise Modeling Handbook: Resource Guide for Coastal Land Managers, Engineers, and Scientists. Professional Paper.

FENG Y. & ZHAN S. (2011), Simulation of Real Water in 3D Animation. 2011 International Conference on Multimedia Technology.

FRAZIER, T., WOOD, N., YARNAL, B. & BAUER, D. (2010), Influence of Potential Sea Level Rise on Societal Vulnerability To Hurricane Storm-Surge Hazards, Sarasota County, Florida. Appl Geogr. (in Press, corrected Proof). doi: 10.1016/j.apgeog.2010.05.005.

HILL, K. & BARNETT, J. (2007), Design for Rising Sea Levels. Harvard Design Magazine, 27, 14-17.

JELESNIANSKI, C. P., CHEN, J. & SHAFFER, W. A. (1992), SLOSH: Sea, lake, and Overland Surges from Hurricanes. NOAA Technical Report NWS 48, National Oceanic and Atmospheric Administration, U. S. Department of Commerce, 71.

LEVIN, L., BOESCH, D., COVICH, A., DAHM, C., ERSÉUS, C., EWEL, K. C., KNEIB, R. T., MOLDENKE, A., PALMER, M. A., SNELGROVE, P., STRAYER, D. & WESLAWSKI, J. C. (2001), The Function of Marine Critical Transition Zones and the Importance of Sediment Biodiversity. Ecosystems, 4, 430-451. https://doi.org/10.1007/s10021-001-0021-4.

MELSOM, J. GIROT, C. & HURKXKENS, I. (2015), Directed Deposition: Exploring the Roles of Simulation and Design in Erosion and Landslide Processes. ACADIA 2105, Computational Ecologies, Design in the Anthropocene, 211-221.

NICHOLLS, R., WONG, P., BURKETT, V., CODIGNOTTO, J., HAY, J., MCLEAN, R., RAGOONADEN, S., WOODROFFE, C., ABUODHA, P., ARBLASTER, J., BROWN, B., FORBES, D., HALL, J., KOVATS, S., LOWE, J., MCINNES, K., MOSER, S., RUPP-ARMSTRONG, S. & SAITO, Y. (2007), Coastal systems and low-lying areas. In: PARRY, M. L. et al. (Eds.), Climate change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II To The Fourth Assessment Report Of The Intergovernmental Panel On Climate Change. Cambridge University Press, Cambridge, 315-356.

SALGUEIRO, I. B. & FERRIES, B. (2015), AN "ENVIRONMENTAL BIM" APPROACH FOR THE ARCHITECTURAL SCHEMATIC DESIGN STAGE. International Journal of Architectural Computing, 13 (3-4), 299-312. https://doi.org/10.1260/1478-0771.13.3-4.299.

SHEPPARD, S. (2015), Making Climate Change Visible: A Critical Role for Landscape Professionals. Landscape and Urban Planning, 142, 95-105. https://doi.org/10.1016/j.landurbplan.2015.07.006.

SPAULDING, M. L., GRILLI, A., DAMON, C., CREAN, T., FUGATE, G., OAKLEY, B. A. & STEMPEL, P. (2016), "STORMTOOLS: Coastal Environmental Risk Index (CERI)." J. Mar. Sci. Eng., 4 (3), 54 ff.

WATSON, D. & ADAMS, M. (2011), Design for Flooding: Architecture, Landscape, and Urban Design for Climate Change (1st Ed.). John Wiley & Sons, Chichester.

ZASPEL, P. & GRIEBEL, M. (2011), Photorealistic Visualization and Fluid Animation: Coupling of Maya with a Two-phase Navier-Stokes Fluid Solver. Computing and Visualization in Science, 14 (8), 371-383. doi:10.1007/s00791-013-0188-1.