Hybrids & Haecceities

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Tactical Sedimentation of Architectural Reef System

Hybrid simulation framework for nearshore underwater landscapes

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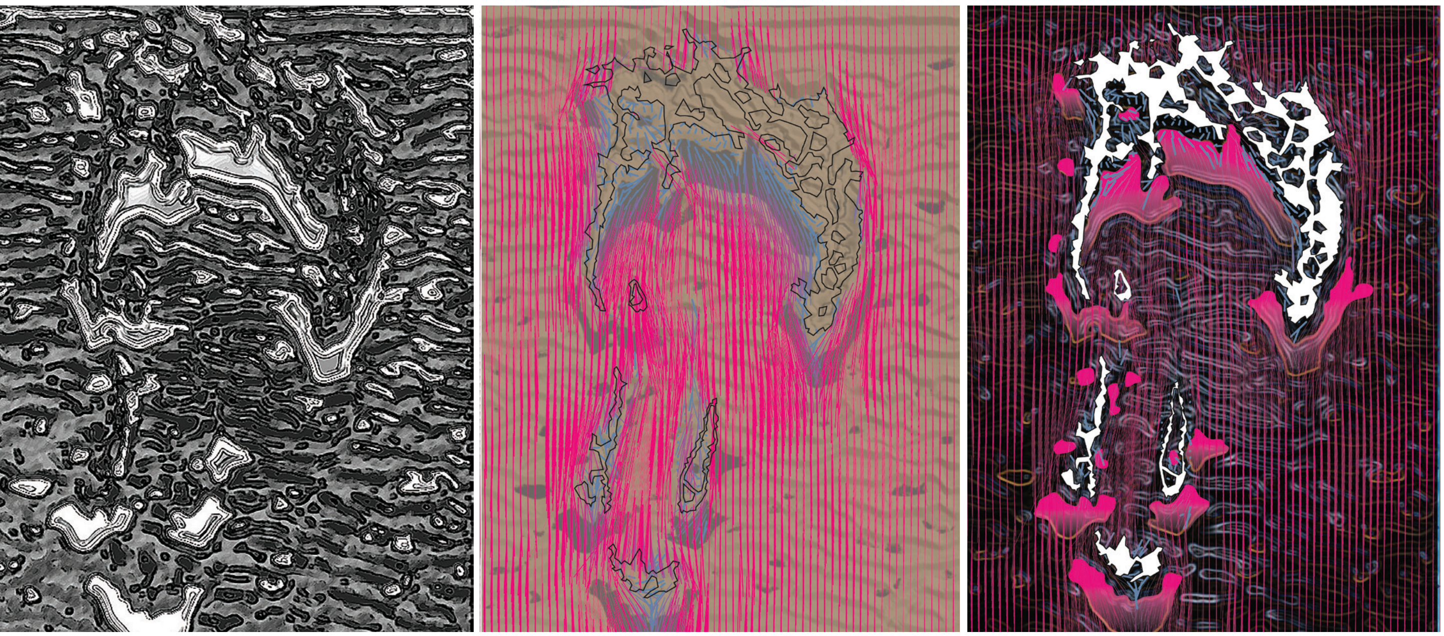

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1 Analysis workflow of overlaying digital CFD and sediment movement simulations to evaluate potential areas for safe sediment accumulation to enhance coral growth

ABSTRACT

Coral reefs are rapidly dying due to climate change and anthropogenic activities. Because these sensitive ecosystems are critical to ocean health, new approaches for designing synthetic reef systems have emerged in the last 50 years to sustain and promote coral diversity. However, despite their success, these studies lack the larger-scale and higher-level ecological analysis that accounts for anthropogenic threats to these ecosystems. Without considering how contemporary near-shore environments are hybrid, novel landscapes, artificial reefs are not designed for shared ecologies. This study proposes a novel simulation framework that expands the existing analytical modeling methods, allowing us to visualize and test underwater eco-spatial phenomena within dynamic systems to better identify a design space for intervention with the goal of mitigating the conventional human-reef relationship through tactically choreographing sedimentation. This paper focuses on developing a method of modeling and analysis linked to the ecological characterization of coral species and simulation sequences allowing us to: 1) study diverse, underwater landscapes that are not easily visible or accessible, and 2) project complex environmental change and sedimentation over time. This method works across tools, scales, and media to develop a computational ecological approach to designing sensitive habitats. Our simulation sequence proposes an overlay of (a) CFD analysis with (b) computational sand dune formation and (c) physical experimentation using a simulated sand and water table to study the sediment response to morphological intervention. The goal is to identify zones of intervention within the dynamic underwater landscape that encourage strategic increase or decrease of sediment build-up, nurturing coral health. This method creates a strategic, responsive framework for a site-specific coral reef typology that enables a deeper understanding of dynamic environments.

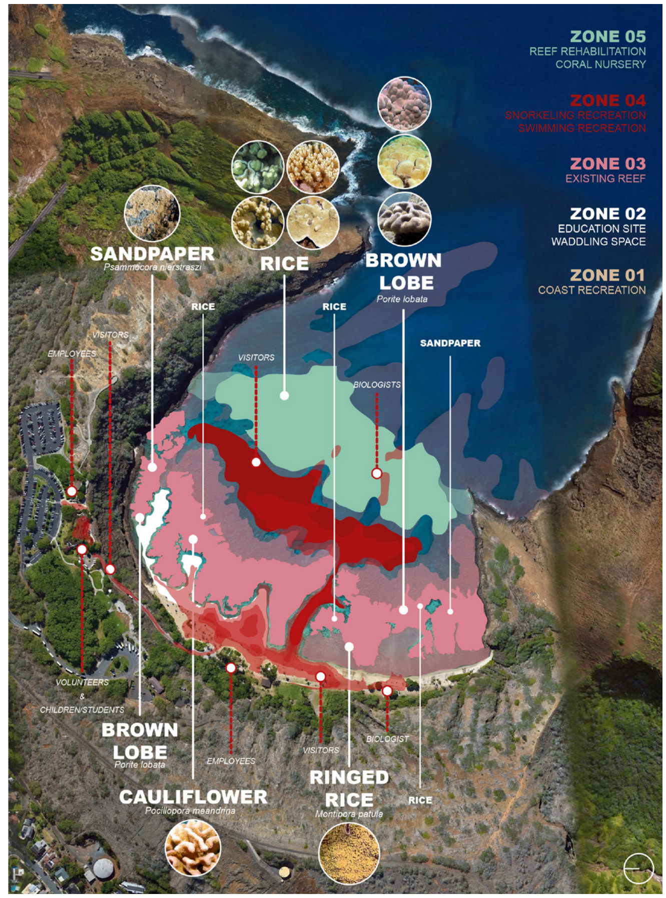
INTRODUCTION

Coral Reefs are known as the "rainforests of the sea" because of the diversity of life that is found within them. They are one of the most diverse, valuable ecosystems in the world, supporting more species per unit of area than any other marine environment (NOAA n.d.). They exist in a variety of shapes and sizes with various morphologies formed throughout time, providing different needs for different species: a place for food, reproductive space, space to care for young, and shelter. There are also many benefits to humans that come with coral reefs; reefs serve as a natural marine barrier to protect coastal communities from high-impact waves during natural disasters, provide food and medicinal resources, and support the economy by increasing job opportunities.

Despite their importance, coral reefs are dying at a rapid pace. Over 50% of the world's coral reefs have died in the last 30 years. Up to 90% are predicted to die within the next century (IUCN 2021). Warming waters, pollution, acidification, overfishing, sedimentation, and physical destruction are some of the causes of coral bleaching and death. Climate change is one of the greatest global threats against coral reef ecosystems. As temperatures continue to rise, disease and coral bleaching become more common in coral reef ecosystems. Undisturbed, it takes approximately 9 to 12 years for a coral reef to recover from a coral bleaching event.

Other than climate change, one of the leading causes of the rapid decline of coral reef health is human activity. Anthropogenic activities are major threats to coral reefs (NOAA n.d.). Pollution, overfishing, harmful fishing practices, collecting live coral for the aquarium market, and mining coral for building materials are some of the many ways that people damage reefs around the world. For example, deep water trawling, which involves dragging a fishing net along the sea bottom, can tangle up and kill reef organisms. Also tourism can create direct, harmful contact with coral reefs when tourists do not understand how to be careful with these delicate ecosystems.

A known method to combat coral reef death is the production of artificial reefs (Hilbertz 2009; POSCO 2000; Moffitt 1989; Faridah 2015). These artificial reefs help to restore fisheries and to mitigate the effects of resource exploitation and destructive practices like trawling. Many artificial reef material case studies around the world have been successful in multiple ways, whether from their strength, the biodiversity they attract, or their effects on coastal communities. However, if they are not installed with sensitivity to the larger underwater dynamic system or designed with a deeper knowledge of the effects of their form and material, they can be destructive to existing reefs. Understanding the underwater landscapes requires complex, often hybrid approaches. More



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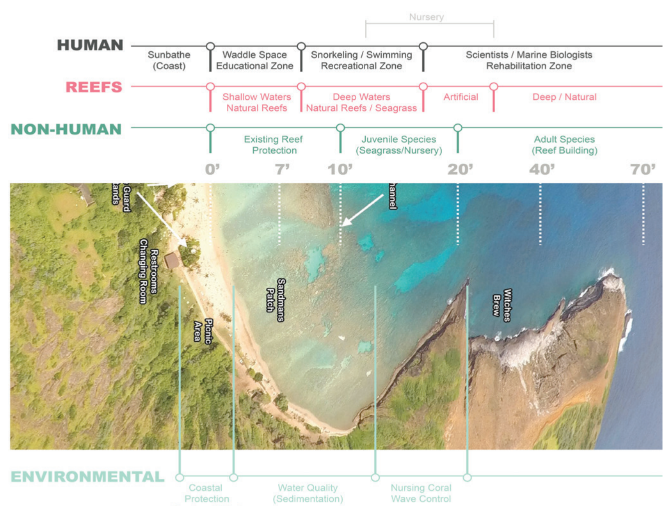

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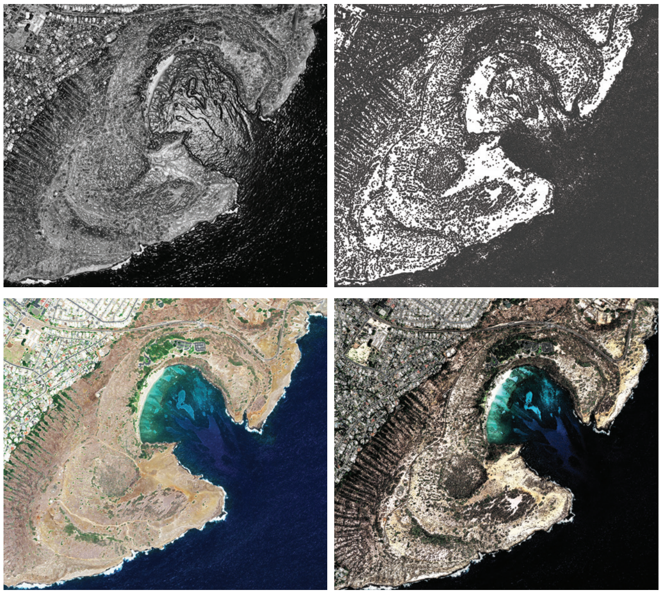
2 Qualitative data gathered on Hanauma Bay looking into the existing coral species and their location on site, human visitor circulation and density, and types of marine creatures that reside in the Bay

3 An analysis on different zonal conditions (education spaces, recreational spaces, and rehabilitative/nursery spaces) that can reside in the Bay based on the gathered qualitative data



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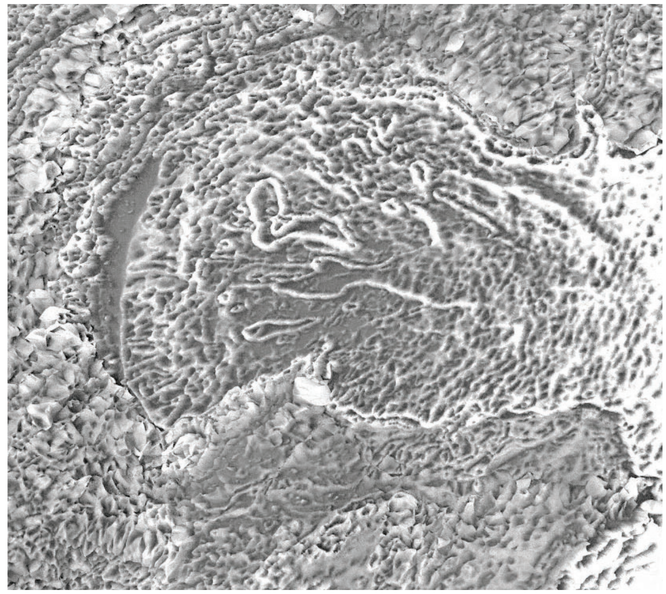

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4 A series of filtered rastered Google Earth satellite images of the site

5 Final 3D mesh generated using depth mapping of coral reef in Hanauma Bay allowing for identification of coral species referenced by field data

6 Re-sketching site organization based on simulated studies focused on computational fluid dynamics of water and sediment movement across the bay to create new pathways for multi-species.

standard numerical/physics-based modeling in nearshore environments is particularly difficult given the turbulence of wave action in the transition zone between land and ocean (Wang 2005). Climate change has increased the stochasticity of these sensitive thresholds and unpredictable human use has introduced further complications. These studies on artificial reefs seem promising. However, many of these studies omit the analysis or acknowledgment of the anthropogenic threat to these coral reefs (Kleypas 2001). This is, in part, because of the lack of non-intrusive methodologies that allow for more nuanced modeling and experimentation within such a sensitive environment to understand the complex interactions between natural forces, humans, and reefs.

THE CASE STUDY SITE: HANAUMA BAY

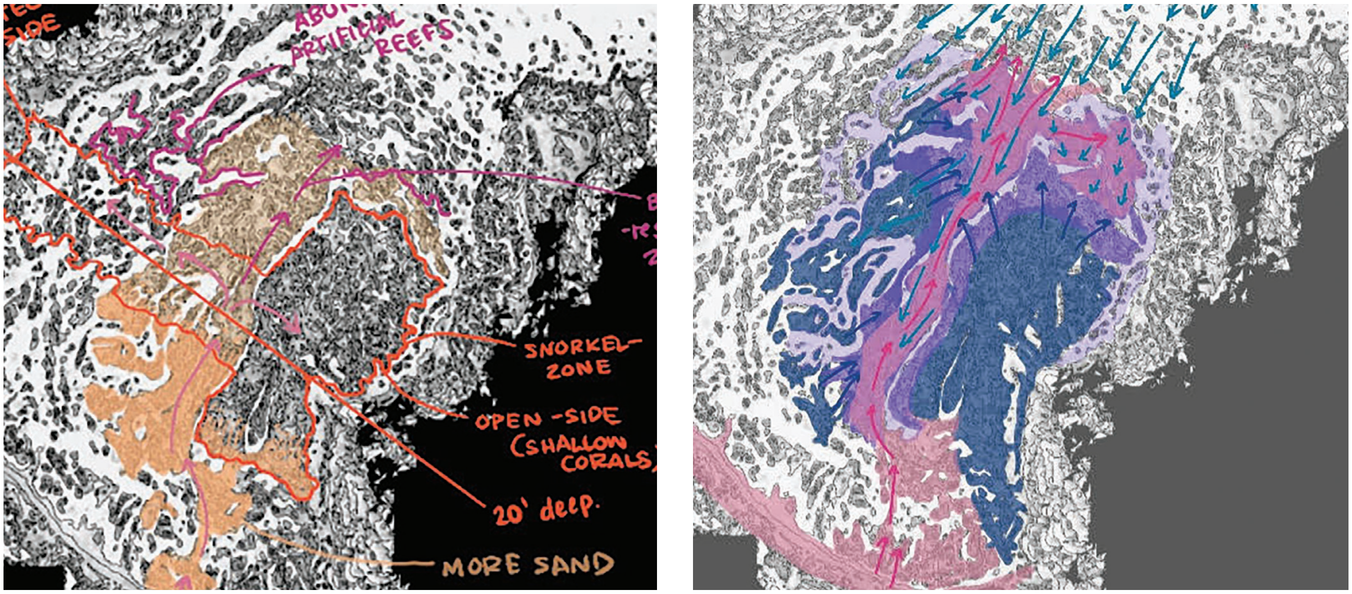
Hanauma Bay in Honolulu, Hawai'i, contains an endangered coral reef ecosystem. This location is a popular tourist destination, which is a large source of income for the Hawaiian economy. However, since this beach was opened to nonlocals, the coral reef ecosystem has rapidly decayed because of both climate change and the impacts of recreational activities like swimming, diving, and snorkeling. Several studies have tried to determine "acceptable limits of human disturbance" to allow visitors to continue visiting without degrading the reef's health. Despite these measurements, humans still impact the coral reef's health, but at a much slower pace, keeping these reefs from fully recovering (Tsang and Stefanak 2020). During this study, dynamic entanglement between all elements and actants on the case study site was mapped to identify the areas of intervention that allow healthy coexistence.

LACK OF DATA: UNDERWATER MORPHOLOGY MODELING PROCEDURE

Initially, past research was collected and mapped to understand the types of visitors—both human and nonhuman—that reside in the bay (Figure 2). The aim of this data collection was to create multiple zonal conditions on site, mapping multi-species connections (Figure 3). These include zones focused on human recreation, rehabilitation, and education, respectively.

The study began by digitally modeling the existing site conditions and coral reefs on site, focusing on the brown lobe, rice, sandpaper, and cauliflower coral species. However, no online database exists for mapping underwater topographies of habitats. Many small islands that house coral reefs, like Hawai'i, lack digital databases due to their small size and secluded locations. There is also no standard method for modeling dynamic over-time relationships between coral reefs and recreational landscapes. To respond to this gap, we propose a method to construct a hybrid digital model for coral reef typology using the scarce online resources.

Resourcing topographical information of Hanauma Bay via CityEngine (ArcGIS n.d.)—which directly utilizes ArcGIS data—an initial 3D model of Hanauma Bay was constructed. Then, it was hybridized by adding additional bathymetric data to model the ocean floor. A cohesive surface model of Hanauma Bay nearshore topography was developed that could be used as a substrate for depth- and texture-mapping of the coral reef morphology.



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To create a specific digital coral morphology, several Google Earth satellite images of the site were enhanced to visualize the shapes of coral textures (Figure 4). Then, this modified image was applied to the 3D site model through a depth-mapping procedure (Figure 5).

Using depth map modeling, a series of 2D rasterized data maps were enhanced and superimposed directly onto the 3D mesh model of Hanauma Bay to spatialize various coral reef ecosystems in the bay (Figure 5). The accuracy of this new 3D mesh morphology directly relates to the resolution of depth-based image channels, which can be partially amplified, even from lower-resolution satellite images. Existing contemporary 3D hydrodynamic models such as CMS Wave/CMS Flow and Delft3D can solve continuity and Navier Stokes equations, or more simply, accurately represent the physics of this context. However, these models 1) rely on robust 3D data sets, which are not available for many sites like Hanauma Bay, and 2) oversimplify the fate of landscapes that have to account for human use. Our proposed workflow can enhance the accuracy of this modeling method with higher-resolution satellite imagery. Using the proposed workflow, this study focuses on identifying the dynamic phenomena of sedimentation patterns relative to diverse coral speciation.

Identifying Strategies for Entanglements: What to Simulate? Species Identification

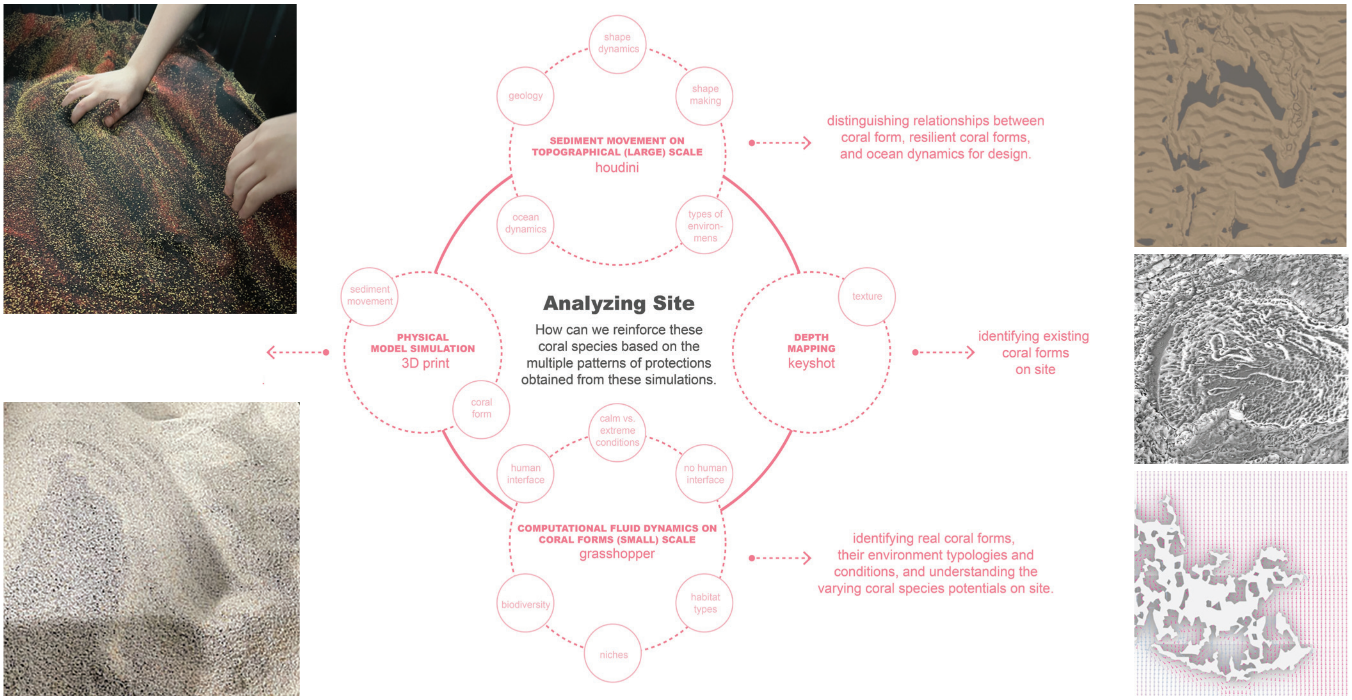
Combining sketches with the newly-developed coral reef morphological model allows for choreographing various human and nonhuman activities to support dynamic formations while allowing the entanglement of pathways for humans and marine creatures to be protected by both artificial and natural coral reefs (Figure 6).

Sedimentation is known to hurt corals; it can lead to suffocation due to suspended sand blocking sunlight or sand settling on corals (NOAA n.d.). However, corals have developed methods to protect themselves from high levels of sedimentation such as secreting protective shields (NOAA n.d.) or evolving into a funnel shape to create "sedimentation traps" (Riegl 1996) to protect other corals that grow on its surface. If designed carefully, sedimentation can actually be accumulated in a way that benefits coral reefs. Due to rising sea levels, corals have been unable to grow quickly enough to gather sufficient sunlight, causing them to starve (Sanborn 2017). Increased sedimentation in certain areas could elevate growing beds on the seafloor as well as encourage vertical coral growth, allowing these coral species to be closer to the sea surface and have more access to sunlight.

These areas of decreased or increased sedimentation can be shaped through artificial reefs placed strategically around the bay in response to the existing natural reef. This can allow us to shape pathways for humans and pathways for marine creatures to safely interact with one another while setting up a methodology for simulation and experimentation in further understanding the conditions of the natural environment acting upon the coral reef in response to safe, tactical areas of increased sedimentation.

Separation of Coral Form for Analysis

To perform these test analyses, the site was divided based on prior research that identified portions of the coral reef differently affected by human activity (Severino 2019). The northern portion is a coral reef located closer to shore with a more dense and resilient form. The southern portion is a coral reef that is more scattered and fragile forming. By using this method, smaller, more typical segments of coral



7 Circle of analysis and simulations focusing on constantly circulating through various simulation (fluid dynamics, sediment movement) and media (digital, physical) to create a constant flow of information that speaks to one another

reef forms could be studied to evaluate how they are affected by natural forces.

This project utilizes architectural methods of modeling underwater morphologies based on accessible satellite images. For higher accuracy of the coral reef topography model, the satellite data was enhanced to intensify the depth channel. This is a partially speculative procedure that is juxtaposed with a more rigorous, scientific method of analysis such as fluid dynamics and sediment movement. Furthermore, the gathered data was expanded and simulated this phenomena into a potential design integration of an artificial reef system that could be implemented on the site.

DIGITAL AND PHYSICAL SIMULATIONS

To begin understanding the conditions of the coral reef in Hanauma Bay, a series of simulations was conducted on the coral reef at various scales, including simulating the natural flows (fluid and sediment movement) and the media (digital and physical simulation) (Figure 7). The goal of this simulation series was to understand the sediment accumulation and disbursement phenomena that begin to reinforce particular coral species based on the multiple patterns and scales of protection as well as to understand how digital and physical simulations compare.

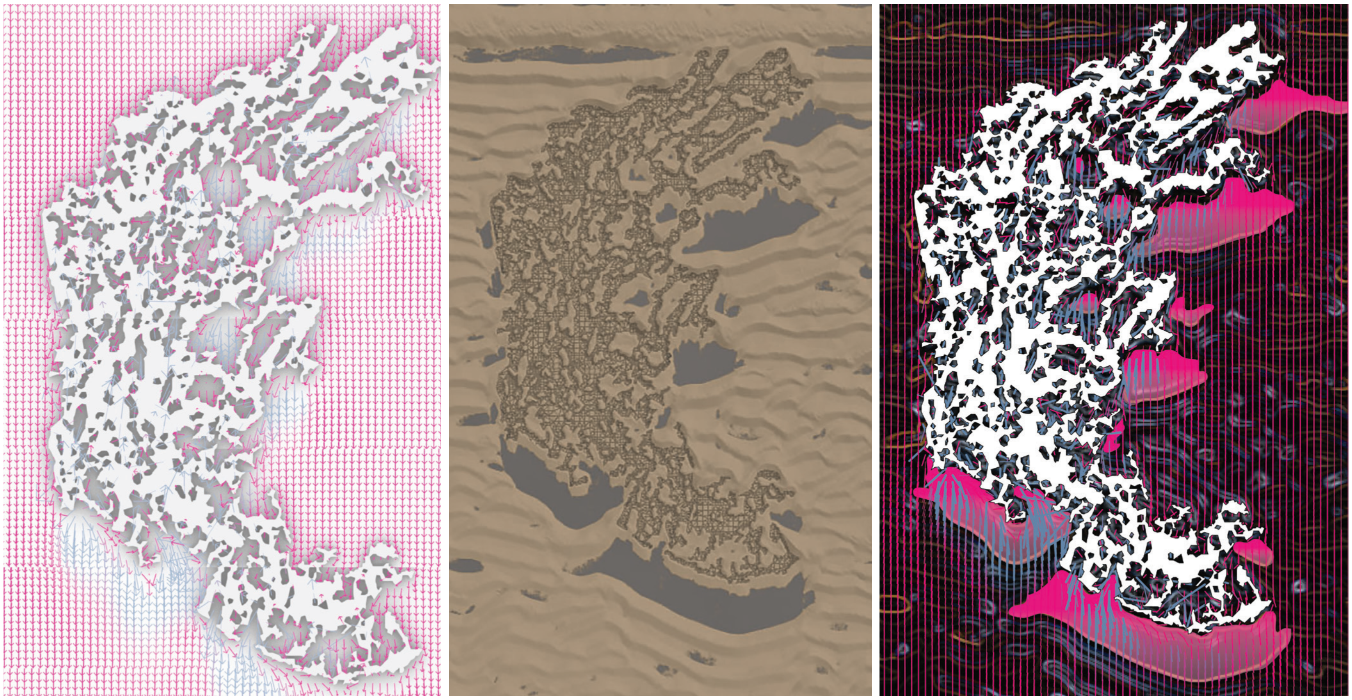
Computational Fluid Dynamics: Water Flow

Computational fluid dynamics (CFD) in Rhino-Grasshopper-Butterfly was used to examine the movement of water forces on the existing coral form (Simscale n.d.). The CFD simulations ran through the two large coral reef sections on site using an average wind speed (pink lines) of 10.3 mph and a low wind speed (blue lines) of 3.4 mph (Figure 8). The blue lines created a shadow of the overall coral form that highlighted where the slowest water movement occurred.

These CFD simulations show a "formal shadow," which was created by the water hitting the coral (Figure 8). This shadow contains the area with the slowest moving water. These shadows potentially allow for an area that could be built up to enhance coral growth. Additionally, these areas could be redesigned, adding structures to carefully increase water speed in specific areas. Corals are known to thrive in fast currents, so this analysis can locate intervention areas to increase water speeds in specific areas of the bay, especially zones focused on rehabilitation.

Sediment Movement

Sand sedimentation simulations focused on observing how sediments collect in various areas surrounding a coral reef and looked for potential areas in which it could carefully accumulate, and encourage vertical growth in the coral reef. Vertical coral growth is a series of evolutions that corals have undergone to avoid trampling, specifically on sites that are heavily populated by humans. Hanauma Bay has an abundance of vertical corals because of the high human activity that occurs. However, sediment accumulation must be thoughtfully choreographed; too much sand could lead to coral suffocation. We



8 Workflow of conducting CFD simulations and sediment movement simulations then overlaying the two results on top of one another to locate potential areas for safe sediment accumulation

must design carefully to maximize the benefits of sediment accumulation, encouraging vertical coral growth.

Houdini-dune solver was used for this analysis. Dune solver (LP) (Meeker 2021) is an asset for Houdini created by Barrett Meeker. It is a height field and terrain tool that simulates the ways sand dunes are formed from wind, sand depth, and other factors.

These experiments visualize a trend of locations with little to no sand that could be redesigned for safe sediment accumulations. These sandless areas are potential locations for careful sediment accumulation to encourage coral reef growth on higher grounds.

Applying Shadows: Overlaying Digital Simulations

The CFD and sediment simulations were overlaid to investigate the relationship between the two sets of data and to discover potential areas for land building or speeding up and slowing down water to enhance coral growth (Figure 9). Using these simulations, potential areas were identified for high sand densities informed by both the coral form and the open ocean floor (Figures 9, 10).

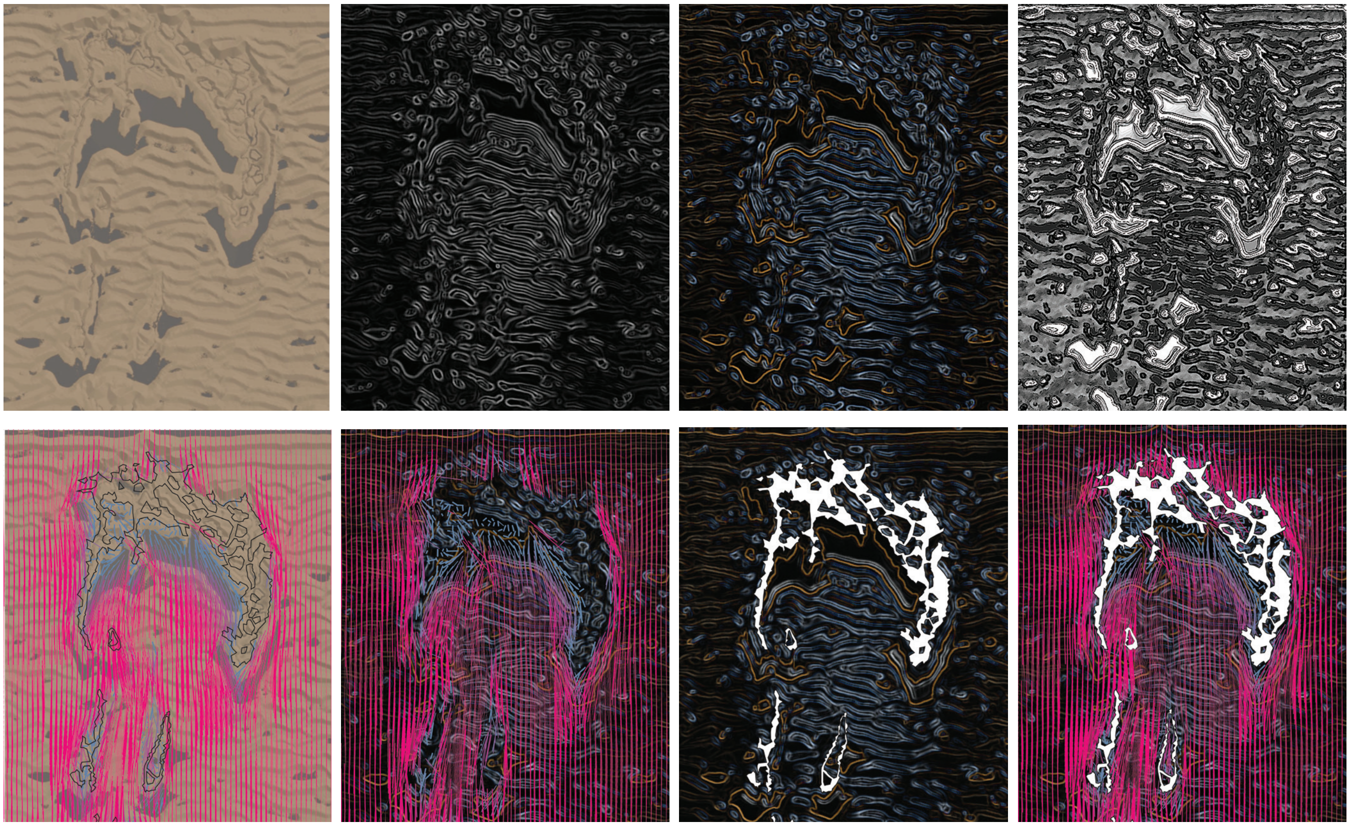
The simulation overlap revealed more complex sediment movement and water flow patterns, identifying shadows from the coral form. These shadows are potential areas for an artificial reef placement to enhance coral growth. More nuanced simulation on a smaller scale could also reveal formal characteristics for soft artificial reef barrier designs.

Such soft artificial reef barriers help accumulate sand at an angle driven by the water direction, allowing for corals to grow vertically. This strategy would bring the coral reef closer to the ocean's surface, allowing them to better collect sunlight while also raising awareness of their location to any visitors nearby to avoid trampling. Also, these barriers must be large enough to safely separate humans and the fragile coral reefs to allow them to grow undisturbed.

In addition to informing these self-forming, localized interventions, the shared simulation effects reveal the natural forces that occur in interaction with the coral reefs; these forces can help support the production of new lands through sediment accumulation, thus encouraging a positive relationship between multiple species as well as a more biodiverse environment.

Physical Simulations with Mixed-media Sediments

The physical simulations with the water table (Figure 11) and engineered sand (Figure 12) focused on sediment movement by comparing the results of the digital and the physical simulations. The overlaps between the two sets of simulations contributed to identifying more nuanced sedimentation phenomena and aided in the process of designing artificial reefs that can accumulate amounts and forms of sediment. Initially, several simple shapes were tested in the water table to establish a baseline for the comparison of digital and physical simulations (Figure 13). Digital simulations have a more uniform set of information due to the constant water speed and flow that moves across the entire surface, while physical



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9 Enhancement and overlaying of the two conducted simulations, CFD water flow and sediment movement, to bring out the patterns of information shown

10 Analyzing coral reef shadows as potential spaces for sediment collection and growth from the overlaid simulation results

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simulations create a more concentrated flow because of the single-point water source.

Overlaps of information show the shadow of sediment accumulation (Figures 14). The darkest areas shown in the simulation (outlined in red) show the locations with the largest potentials for sediment accumulation. The brightest areas (outlined in green) showcase where the accumulated sediments could grow over time. This information could help create a standard for different types of artificial reef forms, shapes, and placements on the seafloor to respond to this data set for safe accumulations of sediments for coral growth.

"Shadows" represent potential areas for increased or decreased sedimentation in relation to the existing natural reef topology. These shadows identify areas of safe sediment accumulation or areas that may have too much sedimentation for optimal coral reef growth. Sedimentation can be regulated in areas where there is more existing sediment build up (darker portions of the simulations) to reduce coral drowning caused by increased sedimentation. Increased sedimentation can be designed in spaces that have less sedimentation as

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11 Sand table set up for physical simulation testing using two (36 in x 24 in) utility tubs, one solar hot water heater circulation pump with DC power supply adaptor (low noise, 3 m head, 8 LPM, 2.1 GPM), two (1/2 in ID x 3/4 in OD x 25 ft long) clear PVC flexible vinyl tubing, four plastic barbed hose fittings (3/8 in adapter hose ID, 1/4 in NPT male), four plastic pipe fitting (straight connector, 1/4 in NPT female threaded pipe), and three screw tops that filter water.

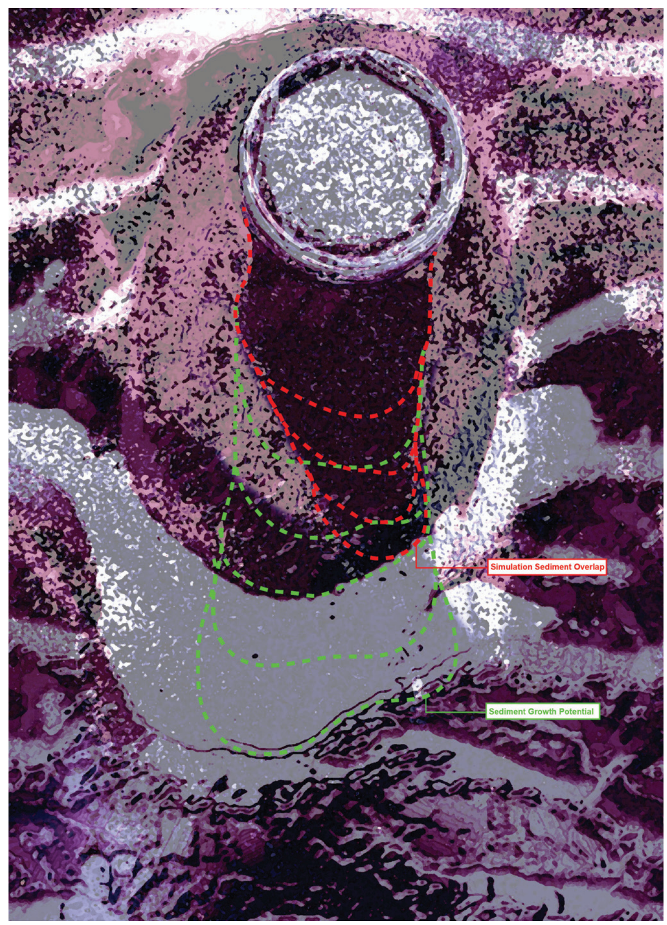
12 Emriver (Emriver n.d.) color-coded media sand mixture. The color-coded media allows for easier visualization of the sediments being transported according to their grain size. The sizes are approximately 1.4 mm for the yellow particles, 1.0 mm for white, 0.8 mm for black, and 0.4 mm for red.

13 Physical and digital simulation results enhanced for further analysis

14 An overlap of physical and digital simulations, looking at various areas and levels (dark vs. bright) of overlap to determine spaces safe for sediment accumulation

a result of the coral form (the lightest portions of the simulation) to elevate seabeds and raise up corals so they can gather more sunlight.

The simulations identify a potentially interesting phenomenon that is not typically considered. The simulations allow us to map a multitude of scenarios for sediment accumulation between coral morphology and water behavior. However, identifying these patterns should not be thought of as a 'final result,' but rather an alternative approach to generating a coral growth strategy in the context of human engagement.



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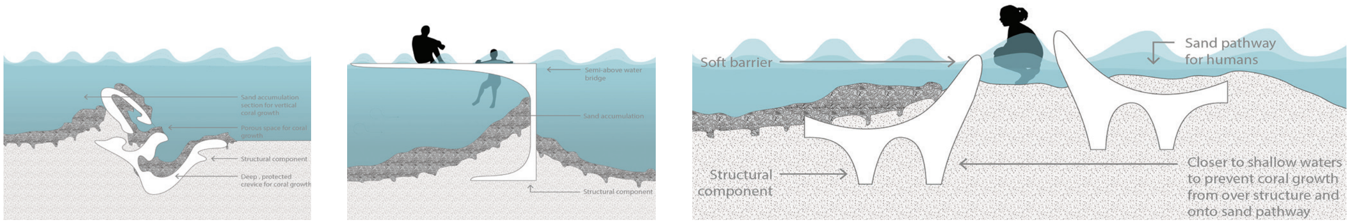

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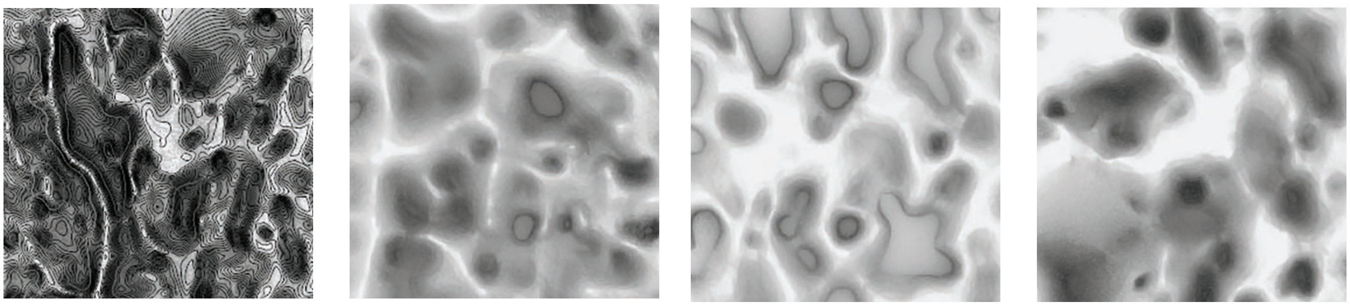

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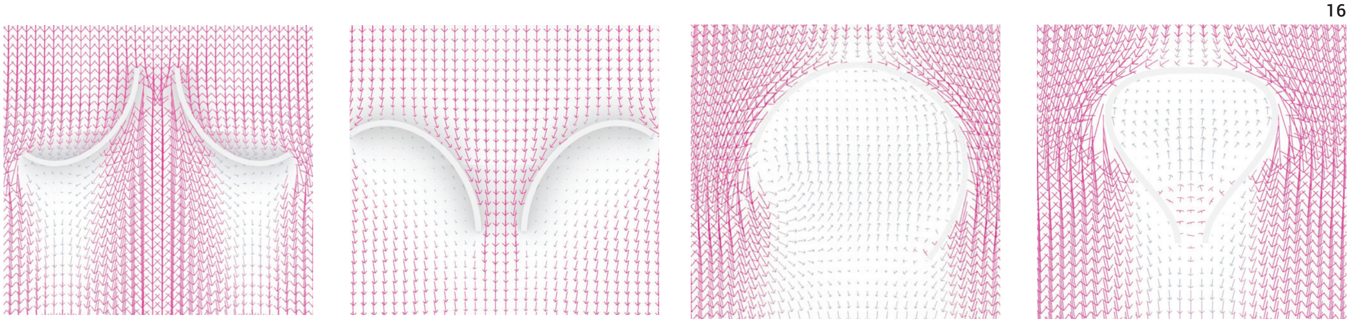

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15 Proposed designs of artificial reef barriers and bridges focused towards developing new lands to create pathways safe for human-nonhuman interactions, enhancing coral growth, creating visual and physical barriers, and the encouragement of vertical coral growth while grounding itself deep into the sea floor to increase resilience against strong natural forces created in underwater conditions.

16 3D depth mapping rugosity models of coral species that reside in Hanauma Bay (brown lobe, rice, sandpaper, cauliflower)

17 Additional studies on forms that create water tunnels with increased water speeds, water barriers with slower moving water, and water vortexes to trap and clean out sediments.

RE-SITUATING SIMULATION RESULTS ON SITE

Designing New Lands

The results of the various simulations (digital fluid dynamics, digital sediment movement, physical sediment movement) were combined and superimposed onto the Hanauma Bay coral reef model to study the potential for the formation of new land.

By gathering the collective data from previous experiments, new circulation patterns were observed that overlapped existing coral reefs, human pathways, and areas of potential new land. These aspects of sedimentation suggest new potential zones for education, recreation, and rehabilitation. Thus, artificial reef designs can be created that are focused on more specific activity types in specified zones.

Design Integration and Testing

Utilizing the information gathered from the simulations and observations, specific trends were identified that support a more diverse design of artificial reefs and land building. The goal is to understand and adapt to the speed and direction of water movement relative to specific coral morphologies. The aim is to strategically move and collect sediment to support the reef ecosystem.

Two sectional design typologies were developed for artificial reefs in this study: a barrier and a bridge. A barrier is a localized structure embedded into the sea floor that accumulates a soft pile of sediment around it. Besides accumulating sand, it functions as a physical and visual barrier to protect fragile corals and encourage vertical coral growth. On the other hand, the floating bridge extends to the surface of the water and utilizes surface rugosity and porous textures to increase biofouling (Figure 16).

The sectional strategies of a barrier and a bridge should be coupled with planar forms that perpetuate sediment movement in the horizontal plane. A series of potential formal strategies emerged based on the simulation results (Figure 15), including forms that support coral growth, protect corals, accumulate sediments, and allow for safe cohabitation between humans and nonhuman species. This is a hybrid formal framework that utilizes adaptive modularity; these artificial reefs are shaped bespokely and are placed strategically across the bay as well as around the coral reef to speed up, slow down, or redirect water currents (Figure 17).

RE-IMPLEMENTING DESIGN ONTO THE SITE

The Zones

We propose a series of overlapping zones on site: an educational zone, a recreational zone, and a rehabilitation zone (Figure 17). This design moves away from the traditional idea of mixed-use programming used in architecture, and begins to create hybrid dynamic fuzzy zones for multi-species engagement. Moving away from the typological segregation of public and private spaces in terms of marine creatures and coral reef ecologies for humans, this project prioritizes creating safe spaces for multiple species to interact without entirely separating them. The idea of 'private' is centered around creating specific areas that are directed towards rehabilitation and research rather than exclusion. This creates 'safe public spaces' for humans, coral, and marine species to interact. These proposed strategies inspire us to rethink how these artificial reefs could construct self-maintaining, regenerative architectures for sensitive landscapes. There is an abundance of different architectural typologies with the potential to further enhance coral reef growth.

RESULTS

As a tourism-heavy site, Hanauma Bay would benefit from an architectural reef-artificial system intervention. This system allows the rehabilitation of natural coral reefs, attracting increased biodiversity as well as allowing humans and marine species to safely cohabitate. To do this, a novel method of combining quantitative and qualitative data was created to enhance design intervention in dynamic underwater landscapes.

By developing a method of modeling this hybrid topography, one can begin to understand the natural energetic forces that act upon an underwater ecosystem like a coral reef through both digital and physical tests. The digital model can be used to analyze forces such as sediment movement, water speeds, and flows that move across the site. Then, this information can be expanded and analyzed to compare with the physical simulation studies done on sediment movement and the analysis of how these forces act upon simple shapes and forms other than the complexity of a coral reef. This information leads to a more developed model for designing artificial reefs that respond to the needs of the specific ecosystem that is in recovery.

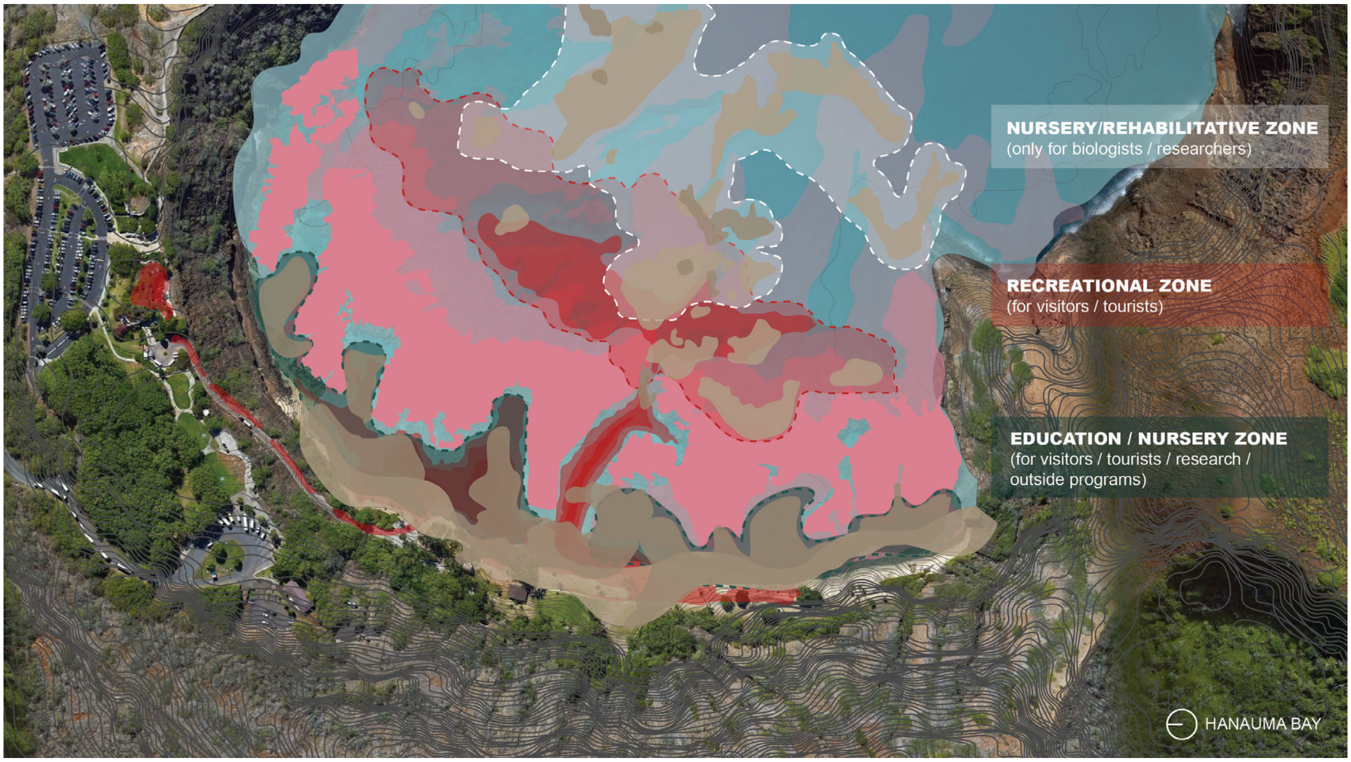
From these simulated studies, new ideas were discovered for controlling these energetic forces by accumulating sand to create new lands as well as slowing down or speeding up water flows to grow coral reefs. It has been previously shown that fast-moving water greatly benefits the growth of coral reefs while sedimentation has been known to have detrimental and potentially positive effects on coral reef growth. If controlled properly and carefully, sedimentation can be effectively used to encourage vertical coral reef growth, which would be tremendously beneficial in an area that is highly populated by humans; this would lead to corals being less susceptible to death from trampling. These raised areas also allow for corals to respond better to rising sea levels, supporting increased growth at higher elevations and increased sunlight collection; they would collect more sunlight quicker than they can naturally grow to match the rapidly rising sea level. Though subsequent in situ physical testing is necessary to validate the simulation results collected in this experiment, this study identifies a design strategy for cross-species zonation. The methods developed in this study can be used to identify potential areas for safe sediment accumulations as well as areas that would most benefit from fast- or slow-moving water based on the various coral species present.

As a result of this study, a diverse set of design interventions was created that focus on a floating bridge typology and a soft barrier typology. These two reef architecture types propose the added benefit of textured surfaces to encourage biofouling, porous spaces to create a difference between interior and exterior surfaces for growth, and the ideas of accumulating different amounts of sand or controlling the speeds of water through the use of modularity. Such artificial reefs would be strategically placed across the bay to enable hybrid activities within each zone: the educational zone, the recreational zone, or the rehabilitative zone; the goal is to create an environmentally friendly landscape that enables regenerative relationships between multiple species.

The modeling method using depth map texture modeling with satellite imaging offers instant visualization of existing habitat while massing and patterns can be updated over time as new growths emerge. The limitation of this cyclical feedback is that the textural maps must be periodically remodeled to reflect shifts in topographies in relation to natural forces and/or human recreation and use. This method has greater accuracy with evolving data accessibility. Additionally, it can be expanded with additional scientific information. It also allows for a more integrated design approach across multiple dynamic forces, bringing together physics with the human and habitat considerations.

CONCLUSION

This study proposes re-evaluating methods for creating responsive hybrid architectures that encourage positive



18 Overview of the different types of zones, activities, and visitors that take place in Hanauma Bay with the implementation of artificial reefs building up new lands

interactions between multi-species environments within dynamic underwater and nearshore landscapes. By studying site-specific coral reef species and their morphologies, new representations emerge that help us uncover data-rich dynamic phenomena for tactical sediment accumulation and land building. Proposing a workflow that uses accessible means of digital drawing, modeling, and simulation to visualize dynamic behaviors relative to larger ecological impacts is critical in the current context of design for climate change. Focused on identifying the area for intervention in outlining a potential design brief for aquatic architectures, a method was proposed looking into an overlap between digital and physical procedures for emerging design strategies. In this study, methods for creating a series of digital and physical simulations was developed to inform the design process based on limited site data. By comparing the results from the digital and physical studies, a better understanding between the distinct formal languages of the natural forces that act upon these sensitive landscapes and of sedimentation can help redefine the strategic placement of design interventions with a more tactical approach to ecological design.

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IMAGE CREDITS

All drawings and images by the authors.

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