Hydraulic Modeling as Craft

The dominating theories within architecture, landscape, and urbanism have been deeply influenced by new paradigms in ecology, complex systems theory, and thermodynamics—shaping design strategies to become dynamic, indeterminate, adaptive, and emergent within the shifting and often volatile landscape of the contemporary. This body of thought has proliferated within a culture of digital technologies—influenced by the availability of technology and the discourse it engenders.

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The past three decades of expanding technological capability has warranted the attention and the experimentation by environmental design fields, however, within areas of urbanism, landscape urbanism, and ecological urbanism, the agenda for designing within complex and chaotic environments will remain speculation until a true material practice is developed. Largely, design inquiry and representations within this camp have done just the opposite, prioritizing systems over material consequences, favoring distillation over physical artifact.

Architectural methods of modeling have moved away from material craft to digital modeling practices, and more recently, to the translation of digital models into material objects through rapid prototyping methods. The output of rapid prototyping, most notably 3d-printed models made with singular materials or the reductive carving of materials by CNC milling, essentially produce "3-dimensional images," says Malcolm McCullough in his book *Abstracting Craft: the Practiced Digital Hand*.[1] Because the production of the fabricated object bears no weight on the performance of the material, the model in turn has no material relationship to what it represents. There is a growing body of research for testing the suitability of architectural materials with fabrication technologies to embed responsivity to their environments; this genre is referred to as "material computation," led by Achim Menges who was recently the editor for the *Architectural Design* issue, "Material Computation: Higher Integration in Morphogenic Design."[2] His extensive work with wood veneers in his Performative Wood Studio explored material properties enhanced by aggregation to create responsive and performative designs. This marks an important shift for understanding materials for their performative capabilities and not just for their permanence or stability. While these structures have the potential to advance responsive climate control and heighten awareness about localized environmental conditions, they do *not* have the ability to adapt. This is where many of the responsive projects in architecture find their limitations. This body of work is indicative of Architecture's translation of technological capacity into *smart* or *intelligent* materials. This paper argues that there is far more complexity and agency in landscape materials than we are currently able to harness within the dominating paradigms of architectural design. It is time to swing the pendulum, rather dramatically, into the realm of materials, and explore the messy practices of material agency.

The relationship between rivers, coasts, and cities is an old one. The interface between human constructed systems and landscape processes will always remain closely connected to hydrology. The contemporary landscape is managed and maintained largely by the control of hydrological systems. From the stable delivery of fresh water and export of sewage, to storm water runoff systems, to navigation and port infrastructure, the management of hydrology is always at play. As hydrologic systems become increasingly manipulated and disturbed from the city scale, to the basin scale, to the watershed scale, the problems are inherently more systemic and more complicated to resolve. Flooding, failures of infrastructure, contamination, and risk in extreme natural weather events only compound these problems. Antoine Picon considers "cities as complex hydraulic systems," in his essay, "Constructing Landscape by Engineering Water," where he states:

> Today, more than ever, hydraulic engineering is paradigmatic for the major issues that concern landscape design as a whole.[3]

A deeper understanding of the interplay between water and the built environment is seemingly the solution, however, the study of hydrologic systems is inherently problematic: "establishing metrics to describe a river's geomorphology is notoriously difficult."[4] Even without the added complexity of anthropogenic influences, rivers are diverse "in terms of their geomorphology, geology, climate, soil development, vegetation cover, [and] land use." When coupled, the specificity, complexity, and dynamism of any given hydrologic system "hinders generalization of observations between different systems and prohibits assumptions of homogeneity within one system."[5]

Increased environmental modeling will improve this field of study, "as areas surveyed by early LiDAR flights (in about the year 2000) will be repeatedly resurveyed, providing geomorphologists with highly detailed, unbiased, wide coverage of topographic changes."[6] While this provides substantial data for bolstering and validating digital models, the added complexity of continuous anthropogenic influence and the chaotic nature of hydrologic systems will always undermine the predictive capability of simulations.

WHY PHYSICAL HYDRAULIC MODELING?

Potamology, 'the study of rivers,' includes river morphology, water movement, and sediment transport. Within this field, physical modeling has always been an important tool for studying hydrologic systems. The existing landscape system is referred to as the *prototype* and the physical model is referred to as the *model*. In the field of hydraulic modeling, digital computational models are referred to as *numerical models*. Technically, both physical and digital models are considered to be forms of computational modeling. As computing power and data-handling capabilities increase, it may seem counter-intuitive that physical models would be preferred over numerical models. However, physical models are quite good at reproducing complex nonlinear physical phenomena which are not yet fully understood, and therefore not available in the form of numerical models. Material and dynamic processes which occur at a large scale often appear at a small scale over much shorter periods of time, quickly revealing complex nonlinear phenomena.[7] Validating a physical model requires mathematical scaling to determine similarity, or similitude:

> In a physical model, the flow conditions are said to be similar to those in the prototype if the model displays similarity of form (geometric similarity), similarity of motion (kinematic similarity) and the similarity of forces (dynamic similarity).[8]

The necessary scaling criteria are difficult to satisfy simultaneously and extracting data from the model may prove difficult (though not as difficult as procuring measurements in the field). Moveable bed models effectively model both fluid and sediment dynamics, which are incredibly difficult to scale in relation to each other and often, result in distorted models, where the vertical scale is exaggerated in relationship to the horizontal scale to achieve similitude. If the model is scaled correctly, the hydrodynamics will perform similarly at smaller scales over shorter periods of time. Numerical models are often used to design and validate physical models and vice versa. The coupling of physical and numerical models is loosely termed *composite modeling*; this practice is "still in its infancy in the hydraulic community" but shows great promise.[9] As sensing technology and computing power advance, the opportunities for extracting model data to develop numerical models as a process of feedback are considerable.

THE MODEL OF THE SEINE ESTUARY

One of the earliest, longest lasting, and most significant contributions to physical hydraulic modeling is the model of the Seine Estuary, a moveable bed scale model designed by SOGREAH, "which began as long ago as 1950, and which continues today with essentially the same model."[10] The Seine estuary is part of the French navigational route for ships headed upstream to the port of Rouen. Intensive siltation, the formation of sills, and shifting channels pose serious navigational challenges along the route and significantly limit shift draft. After the failure of several projects, the authorities recognized the potential value a scaled model might bring:

> The preliminary tests and calibration tests were numerous and complex, and were complemented by a long historical test.[11]

Prior to the completion of the existing model, early hydrographic studies were executed in the area in 1834 and a scaled moveable bed model was built between 1885 and 1895. The works that these early investigations suggested failed due to the limited body of theory surrounding sediment transport and model similitude. While these tests (within the model and the estuary) were considered failures, they provided a foundational framework for physical modeling. The historical surveys and implementation of artificial structures supplied invaluable data about the estuary, which was later used as feedback and validation for the following model iterations.

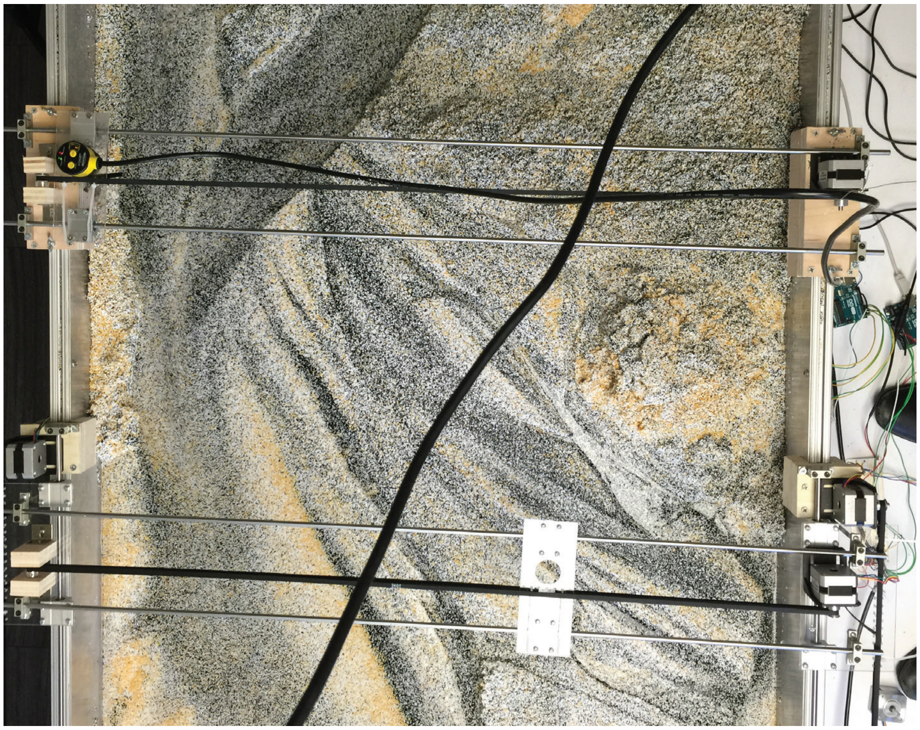
It took more than a year to build the Seine Estuary Model and another 10 months to calibrate it. After the tests manifested stable solutions, the model was validated and maintained:

> As the knowledge of natural phenomena improves, the laws used to interpret them become more complete, but they involve mathematical equations, which contain an ever-increasing number of parameters...The conditions of similitude deduced from these equations become increasingly complex and difficult to reconcile with each other.[12]

The work on the Seine model has thus "shown that the moveable bed model, in spite of the schematic way in which it represents the actual phenomena of nature, is a true measuring apparatus, which is altogether accurate, sensitive, and representative."[13] The model has proven to be a worthwhile investment, particularly within highly managed systems where new works continue to be implemented. The feedback between the management of the landscape, sensed and recorded information, and model simulations (physical and digital) are indicative of the type of design practice necessary for engaging dynamic landscape systems.

THE EXPANDED SMALL-SCALE PHYSICAL MODEL OF THE LOWER MISSISSIPPI RIVER

Dr. Clinton Willson, Professor of civil and environmental engineering is conducting leading research for modeling sediment dynamics along the Lower Mississippi River. The Expanded Small-Scale Physical Model (ESSPM) is a scientific physical model designed to explore the potential for using large-scale river sediment diversions in restoration efforts along the Mississippi River, currently in fabrication at Louisiana State University. Funded by the Coastal Protection and Restoration Authority (CPRA), the model will be an important screening tool



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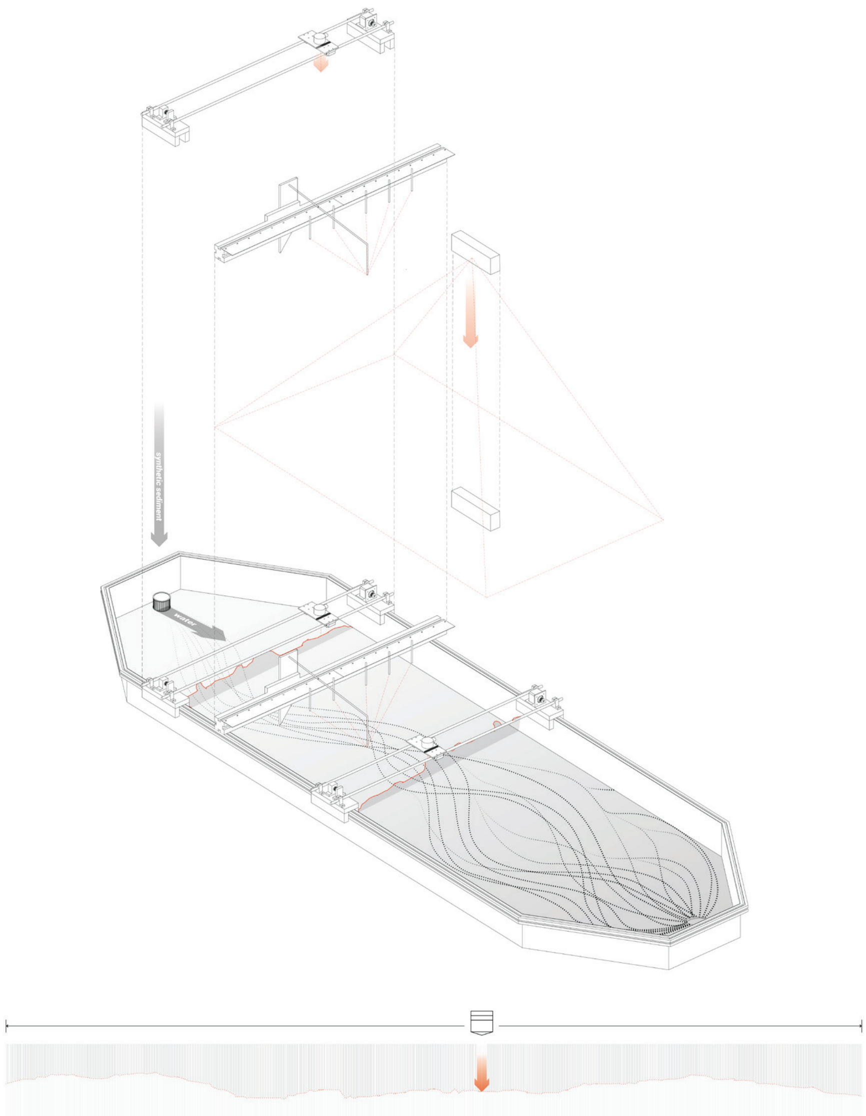
for proposed diversions and river management strategies from Donaldsonville to the Bird's Foot Delta. The ESSPM is considered to be a distorted, small-scale, movable bed physical model, using water and synthetic sediment to simulate the bulk hydraulic and sediment transport processes of the river over much shorter time scales. What would be observed along the Mississippi River in one hundred years of real-time, can be simulated in 50 hours of model time.

In addition to providing important data about future scenarios, the model will serve as a visual communication tool, representing complex runs of choreographed river diversions. In partnership with the LSU Coastal Sustainability Studio and the LSU Cultural Computing and Technology Program, the CPRA will be investing in a state of the art projection system for the model. This system transforms the model into a large projection surface to display tangible and interactive visualizations. These visualizations will be used to communicate the scientific research conducted on the model, describe dynamic systems, and point out areas of interest. In addition to performing as a public communication tool, this interface is utilized by students and researchers at the forefront of their fields, working to develop unprecedented methods of science communication.

Like the Model of the Seine Estuary, the ESSPM is an expanded version of an initial model, called the Small-Sc ale Physical Model (SSPM). The SSPM was made by hand from wood cross sections and high-density foam. Based on elevation data and surveys of the river, cross sections of the river were cut using a bandsaw. The SSPM was constructed, shipped, and reassembled by SOGREAH of Grenoble, France. An organized interdisciplinary team of recognized experts in river modeling, sediment transport, coastal estuaries and coastal geology used the model. A large boom holding a camera was used to capture time-lapse photography of freshwater dispersion over salt-water marsh and the deposition of silt and clay. Most of the operations, measurements, and data collected on the model were done manually. The water was measured with a caliper, the river was dredged with a cooking baster, and sediment was added to the water column using plastic Dixie cups and a stopwatch.[14]

Figure 1: Em River Model sediment bed modified for responsive and interactive design exploration, image captured by the Microsoft Kinect of sediment bed and depth sensors actuated by Arduino microprocessors



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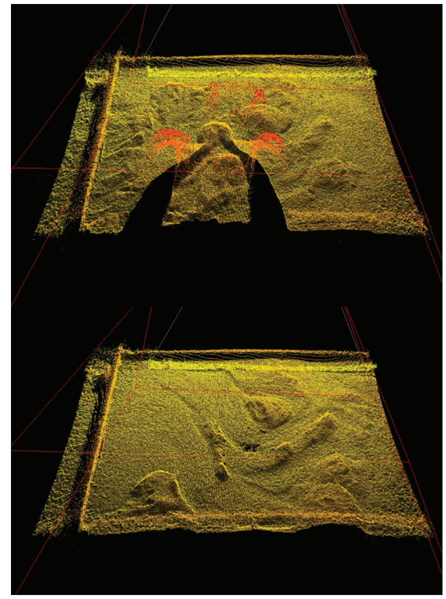

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Figure 2: Diagram of sensing and monitoring devices

Figure 3: Point cloud data of the sediment bed collected by the Microsoft Kinect

THE MODELS OF THE ST. ANTHONY FALLS HYDRAULICS LABORATORY IN MINNEAPOLIS

The St. Anthony Falls Hydraulic Laboratory (SAFL), built across a 15 meter elevation drop on the Falls of St. Anthony in Minneapolis, was designed and built by Lorenz G. Straub to conduct experimental research on the subject of river engineering.[15] The laboratory is filled with interesting and messy models of all sizes, from a tiny model, slowly dropping grains of rice to understand the forces within slopes to one of the largest and most technologically robust models, called the “Jurassic Tank” in part because of its size and in part because it was designed to observe simulations across incredibly long time scales to reproduce extensive and detailed geologic information about the formation of large scale landscapes. The tank is unique in that can simulate subsidence and subtle tectonic movement through a tiled hexagonal based system. The tank holds up to 500 tons of material. After the model is run,

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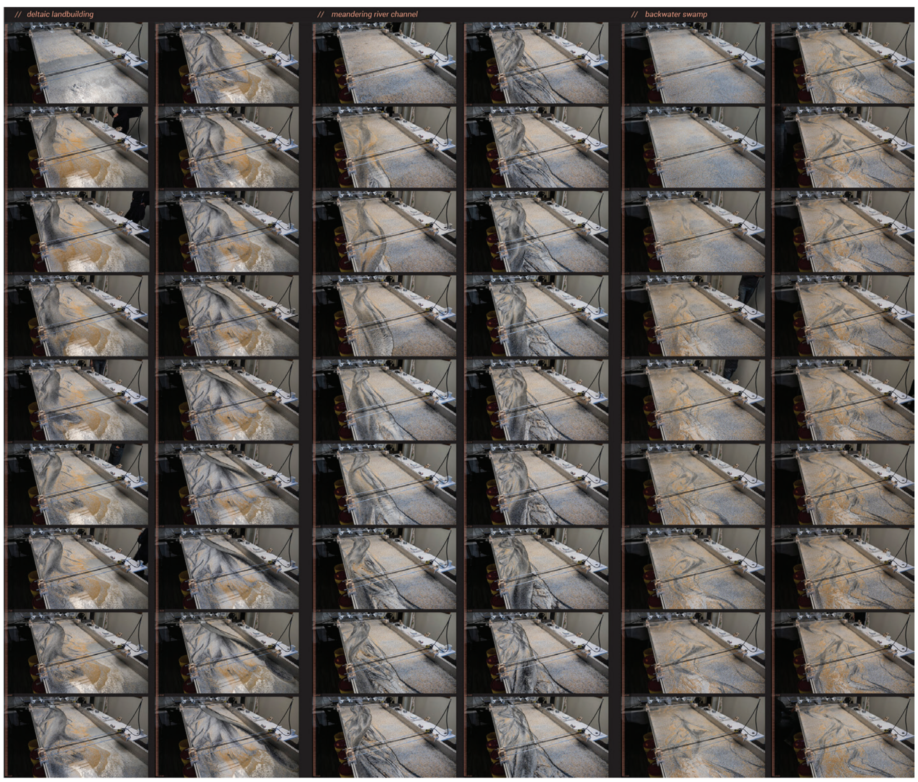

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the researchers allow the sediment to dry and essentially slice the material like an enormous cake, exposing the simulated geologic profile as a section cut. A large strip of plastic with adhesive spray applied to it is pressed against the section to preserve the physical data.[16]

The SAFL is now directed by Dr. Chris Paola, who perhaps speaks the most poetically about physical hydraulic modeling, noting that "there is an irresistible fascination in watching a small, controlled landscape evolve, creating dynamic patterns that seem to come from out of nowhere."[17] His interests in modeling are diverse and extend far beyond the practices of engineering the laboratory was initially founded upon. In a paper by Paola and former directors of the laboratory, they address the question, "What are the major challenges in the 21st Century?" and how can science address them. Their answer:

Figure 4: Depth sensor relay

Figure 5: Abstract landscape typologies established through sediment bed runs

All studies point to the fact that in the face of increasing water demand and other stresses (capital shortages, increasing concerns for the environment, experience of extreme hydrologic conditions), we have to rethink the traditional approaches to water management and take an integrated view of the water cycle and its interaction with the environment.[18]

THE CRAFT OF MODELING

The work presented in the paper thus far, points towards scientific practices of modeling which exhibit a range of messiness and experimentation through a feedback of trial and error. This practice, considered as form of craft with the modeler as craftsman, develops skill through a process of application and assessment—a feedback between intentional manipulation and material response. The effectiveness of these models are dependent on the skill of the modeler, to in certain situations, *know if it looks right*, and to understand, intuitively, how to alter or shift the model to guide results. It is recognized that perhaps in some situations (when it is difficult to establish similarity), the "true value of numerical models may be more nuanced, aligned instead with more qualitative outcomes: for example, predicting what is likely to happen or to have happened, or what direction a river system may take after a given external change."[19]

Paola et al., recognize this as the "unreasonable effectiveness" of physical models, meaning:

> The observed consistency between experimental and field systems despite large differences in governing dimensionless numbers.[20]

This concept for models is less dependent upon reproduction of prototype conditions and more concerned with theories of similarity unbound by scale. In an argument against to continuation of long practiced methods strictly concerned with building engineered structures, Paola et al., propose that a new agenda for landscape experiments revealing "dynamic, self-organized patterns under controlled conditions, and testing theoretical models that engineers of a hundred years ago could scarcely have dreamed of."[21]

METHODS OF PHYSICAL MODELING FOR DESIGN

In the same way that the engineer, scientist, or geomorphologist, must have the experience to read, shift, and guide a model to a state in which it renders meaning, there is open opportunity for the architect to begin to craft their physical modeling skills to resemble and bring meaning to the types of systems and landscapes which present some of the most interesting and exigent issues facing urbanism today. Building upon research and initial prototypes by Bradley Cantrell and Justine Holzman (author), the Responsive Environments and Artifacts Lab at Harvard GSD has recently invested in an Em River sediment table equipped with a digitally programmable media feeder (led by Cantrell). The media feeder is utilized to produce simulated runs or flows across the sediment bed, which become a canvas for articulating designed interventions (Figure 1). The table is rigged with sensing and monitoring equipment for gathering, translating, and post-processing extracted data. The sediment bed is monitored by a Microsoft Kinect overhead to gather imagery while recording surface topography and banner sensors are set on adjustable rails and deployed across the bed with stepper motors (Figure 2, 3).

In this setting, the lab does not have the capacity to calibrate or effectively scale the model to the prototype. The methods for scaling are diagrammatic and illustrative and speak to guiding principles of generalized hydrologic systems. The media feeder—controlling water, synthetic sediments, and dye—and the monitoring equipment are all run using Arduino microprocessors. The microprocessors easily receive input and output extracted data into customized interfaces developed in Rhino with Grasshopper and Firefly as well as Processing.

ENDNOTES

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20. Paola et al., "The 'unreasonable effectiveness' of stratigraphic and geomorphic experiments."
21. Ibid.

With advances in remote sensing capabilities and the trajectory of hydraulic modeling as an exploratory field, there is tremendous opportunity to define design methodologies, which address direct connections between sensed data and physical materials.

This working methodology speaks to potential design workflows and a new method of craft, a method that hinges upon the inherent responsivity of materials. Simulation is, therefore, defined by the feedback between the digital and the physical, a process of inquiry and unfolding as shifting conditions challenge design intentions. The visual impact and potential for physical models to communicate incredibly complex systems and nonlinear phenomena is considered to be a strength in physical hydraulic models. Nonlinear phenomena which appears in complex systems, exists outside of proportional relationships and known mathematical definitions of linear systems. For instance, working with a physical model as opposed to a particle flow simulation in a program such as RealFlow will produce nonlinear phenomena. This form of modeling, as a hybrid between physical materials and the virtualization of those materials, has significant consequence to how the built environment is both known and modified in an age of information, increased intelligence, and unprecedented change.

The work presented in this paper is the framework for building a robust visual language to bridge observed and predicted phenomena between the prototype (the physical environment), the physical model, and digital simulations for the design fields. Models such as this will be the foundation for developing responsive design tools that through methods of human-computer interaction, simulation, visualization, and tangible models, landscape scale issues will become accessible.