Assessing a Fluid Flow Estimation Framework for Coral Reef Reconstruction

Wynona Brinkmann
CREST Lab
Olin College of Engineering
Needham, MA, USA
wbrinkmann@olin.edu

Luca Odio
CREST Lab
Olin College of Engineering
Needham, MA, USA
lodio@olin.edu

Victoria Preston
CREST Lab
Olin College of Engineering
Needham, MA, USA
vpreston@olin.edu

***Abstract*—Understanding fluid flow through coral reef canopies is critical for characterizing nutrient transport, pollutant dispersion, and ecological health. While traditional computational fluid dynamics (CFD) can provide detailed flow predictions, they are computationally expensive and often require large quantities of both geometric and environmental data. This work uses an alternative analytical framework as a case study to evaluate scientific practicality of open-source coral reef meshes and the requirements for operationalizing three-dimensional (3D) reconstructions for environmental analysis. A processing pipeline was created to import, normalize, extract physical parameters, generate digital elevation maps, and estimate in-reef flow velocity. The implementation revealed substantial challenges related to parameter ambiguity, mesh scaling, metadata availability, and reproducibility. Importantly, several variables required by the model (i.e., slope, water depth, and surface velocity) could not be extracted from the geometry tested. These findings suggest that the value of 3D reconstructions for scientific workflows is contingent on standardized metadata, reproducible parameter extraction methods, and environmental context.**

***Index Terms*—3D reconstruction, computational fluid dynamics, digital elevation model, geometric processing**

I. Introduction & Background

Understanding fluid flow through coral reef canopies is critical to characterizing nutrient transport, pollutant dispersion, and ecological health (e.g., [1]). Finding areas of stagnant flow versus turbulent mixing can provide insight into how reefs interact with the surrounding environment [2]. Coral reefs rely on the motion of water to deliver oxygen, distribute nutrients, and remove waste from the system; understanding the flow of water is fundamental to examine the biological and chemical processes at play (e.g., [3]). As photogrammetric reconstruction techniques become common, large-scale three-dimensional (3D) reef models are becoming more accessible and applicable to environmental analysis and monitoring.

In common scientific workflows, 3D reef models are utilized within computational fluid dynamics (CFD) simulations to study reef hydrodynamics; however, while CFD can provide detailed representations of flow fields, it often requires extensive computational resources, specialized expertise, and environmental boundary conditions which may not be readily available. High performance computing (HPC) resources are not globally accessible to reef scientists, conservationists, or natural resource agencies; nor are HPCs practical when rapid analysis or field-based decision making is required. These challenges motivate alternative approaches that leverage 3D reef geometry and reduce computing complexity.

Alternative frameworks to CFD have been explored, including in Pomeroy et al. (2023) [4], which extracts physical parameters from a 3D model of a reef substrate and uses these values as inputs in an analytical physical model rather than a time-based simulation. Their model estimates in-reef velocity using geometric reef properties and a limited number of environmental parameters, evaluated on three broad morphological categories of reef substrate in simulation and laboratory conditions. While the analytical framework still requires environmental information, it replaces the computational and boundary condition requirements of CFD with a reduced set of geometric and environmental parameters.

Recent advances in photogrammetry and 3D reconstruction have largely focused on improving geometric fidelity and visual quality (e.g., [5]). However, downstream scientific analyses often require more than a high-quality mesh, such as standardized metadata, scaling information, orientation, and other derived parameters. This raises the essential question: *what information should accompany a 3D reconstruction for downstream scientific implementation?*

To investigate the practicality of open source meshes, we perform a case study implementing the Pomeroy et al. framework on both synthetic and real-world reef data. We developed a computational pipeline to process reef geometry, derive required parameters, and estimate in-reef flow velocity. This allowed the evaluation of not only applying the framework, but also the broader requirements for operationalizing 3D reef reconstructions as datasets for scientific use. The observations throughout this study have implications on reef modeling, reproducible workflows, validation, and the design and publication of open-source 3D meshes.

II. Method

The analytical framework chosen in this study was developed in [4], which builds on previous work such as [6], and relates the geometry of a given coral reef to the drag force exerted by the benthos to predict β, the ratio of the horizontally averaged in-reef velocity (U_c) to the surface velocity (U_∞). The model operates under the assumption of a slope-driven, current-dominated reef, where the model is built from the quadratic drag law to mathematically isolate the in-reef velocity. The final implemented equation is:

$$\beta = 1 + \frac{u_*}{kU_c} = 1 + \frac{(g(H-h)S)^{1/2}}{k\left(\frac{2\phi gHS}{C_D\lambda_f}\right)^{1/2}} \tag{1}$$

where gravity (g), benthos height (h), water depth (H), surface velocity (U_∞), porosity (ϕ), slope (S), drag coefficient (C_d), total benthos frontal area per unit reef surface area (λ_f), and a proportionality constant (k) define the relationship. Following previous work in this field [8], the drag coefficient was assumed to be constant at 1. The frontal area parameter, λ_f, has multiple interpretations throughout literature depending on the application [9], [10], and here was explored through a parameter sweep and geometric approximations. Porosity and slope were estimated from mesh properties.

For implementation and evaluation, two types of geometries were used: a software generated synthetic reef and a reconstructed real-world coral reef mesh obtained from a publicly available dataset [7]. The synthetic reef consisted of 10,000 randomly generated Cartesian points which use a sinusoidal and Gaussian noise function to produce a structured but irregular terrain shape (Fig. 1). This synthetic dataset allowed for a controlled testing of parameter extraction and implementation logic before it was applied to a real mesh.

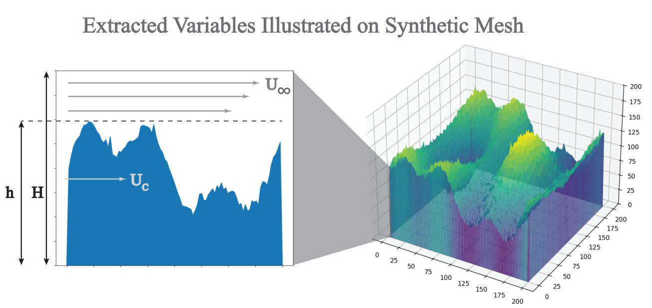

Fig. 1. Visual depiction of water depth (H), height of the benthos (h), surface velocity (U_∞) and in-reef velocity (U_c) using the synthetic reef produced from 10,000 Cartesian points which allows for testing of frameworks and variable extraction before implementing with a real-world reef mesh.

A processing pipeline was developed to prepare both geometries for analysis (Appendix B). A mesh is first imported as a .glb file and merged into a single continuous geometry. To ensure consistency across datasets, the mesh was normalized using a bounding box where the shortest dimension was assigned as the vertical axis and the geometry translated so that the minimum elevation corresponded to the seafloor (Fig. 2). A digital elevation model (DEM) was then generated using a grid as a visual check, from which geometric characteristics defined in the equation could be extracted.

III. Results

The framework yielded physically reasonable trends in predicted in-reef velocity across tested geometries. We encountered two key challenges at time of implementation:

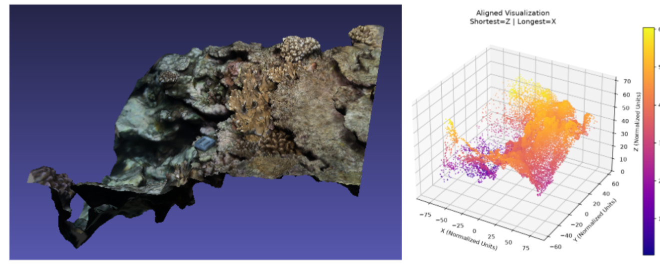

Fig. 2. Mesh of reef as seen in MeshLab compared to mesh visualization post-normalization to ensure alignment.

Variable Ambiguity The parameter λ_f is essential in the model, acting as the primary determinant of flow attenuation. Despite its importance, its definition is ambiguous in the literature [4], [9], [10]. Although every definition of the parameter could be extracted directly from geometric meshes, there is sufficient variation to impact simulation results (Appendix A).

Insufficient Context Several key parameters in the model were simply unavailable from the mesh, such as water depth and surface velocity. Others, such as slope, are partially computable from the mesh, but insufficient context is available: the slope parameter is the water-surface gradient driving the flow [4] and not simply the geometric slope of the reef; the local DEM does not provide the required hydraulic slope and so must be estimated under a set of environmental assumptions. Further, benthos height requires scaling information, often unavailable for the open source meshes we tested.

IV. Discussion & Conclusion

This work investigated a geometry-based reef flow framework as a case study to evaluate the scientific utility of open-source coral reef reconstructions. The challenges encountered support the need to identify and standardize data collection and generative reconstruction workflows for effective post-analysis. Parameters in flow field work, such as frontal area, porosity, orientation, and physical scale, could be extracted using common definitions and included when publishing meshes, and critical environmental conditions (e.g., water depth) recorded within the metadata as a matter of practice. Standardizing the computation and including these quantities would allow for more efficient reproducibility and consistency.

Similarly, a smooth transition between reconstruction formats and analysis tools is of importance. In CFD workflows (e.g., ANSYS) solid, volumetric models are required, but common mesh filetypes are often non-manifold, requiring nontrivial pre-processing that presents a barrier for end-users whose expertise is not within geometry and modeling.

These considerations would allow 3D meshes to function as scientific assets and conservation planning tools. A limitation in our work is that only one real-world reconstruction is being evaluated; future work should examine a breadth of publicly available datasets while also focusing on standardized metadata practices, reproducible parameter extraction workflows, and ways to validate approaches.

REFERENCES

[1] S. G. Monismith, "Hydrodynamics of Coral Reefs," *Annual Review of Fluid Mechanics*, vol. 39, no. 1, pp. 37–55, Jan. 2007, doi: 10.1146/annurev.fluid.38.050304.092125.

[2] K. A. Davis, G. Pawlak, and S. G. Monismith, "Turbulence and Coral Reefs," *Annual Review of Marine Science*, vol. 13, no. 1, pp. 343–373, Jan. 2021, doi: 10.1146/annurev-marine-042120-071823.

[3] C. M. Finelli, B. S. T. Helmuth, N. D. Pentcheff, and D. S. Wethey, "Water flow influences oxygen transport and photosynthetic efficiency in corals," *Coral Reefs*, vol. 25, no. 1, pp. 47–57, Nov. 2005, doi: 10.1007/s00338-005-0055-8.

[4] A. W. M. Pomeroy, M. Ghisalberti, M. Peterson, and V. E. Farooji, "A framework to quantify flow through coral reefs of varying coral cover and morphology," *PLOS ONE*, vol. 18, no. 1, p. e0279623, Jan. 2023, doi: 10.1371/journal.pone.0279623.

[5] A. Arnaubec, M. Ferrera, J. Escartín, M. Matabos, N. Gracias, and J. Opderbecke, "Underwater 3D Reconstruction from Video or Still Imagery: Matisse and 3DMetrics Processing and Exploitation Software," *Journal of Marine Science and Engineering*, vol. 11, no. 5, p. 985, May 2023, doi: 10.3390/jmse11050985.

[6] R. J. Lowe, "Spectral wave dissipation over a barrier reef," *Journal of Geophysical Research*, vol. 110, no. C4, 2005, doi: 10.1029/2004jc002711.

[7] The Hydrous, "Acropora papillare scene," Sketchfab, Sep. 14, 2017. [Online]. Available: https://sketchfab.com/3d-models/acropora-papillare-scene-efdf043f7e0a49a4bafe1ef9556c40fc. [Accessed: Jun. 23, 2026].

[8] C. B. McDonald, J. R. Koseff, and S. G. Monismith, "Effects of the depth to coral height ratio on drag coefficients for unidirectional flow over coral," *Limnology and Oceanography*, vol. 51, no. 3, pp. 1294–1301, May 2006, doi: 10.4319/lo.2006.51.3.1294.

[9] J. Jimenez, "Turbulent Flows Over Rough Walls," *Annual Review of Fluid Mechanics*, vol. 36, no. 1, pp. 173–196, Jan. 2004, doi: 10.1146/annurev.fluid.36.050802.122103.

[10] H. M. Nepf, "Flow and Transport in Regions with Aquatic Vegetation," *Annual Review of Fluid Mechanics*, vol. 44, no. 1, pp. 123–142, Jan. 2012, doi: 10.1146/annurev-fluid-120710-101048.

APPENDIX A
EXAMINING SYSTEM SENSITIVITY TO λ_f

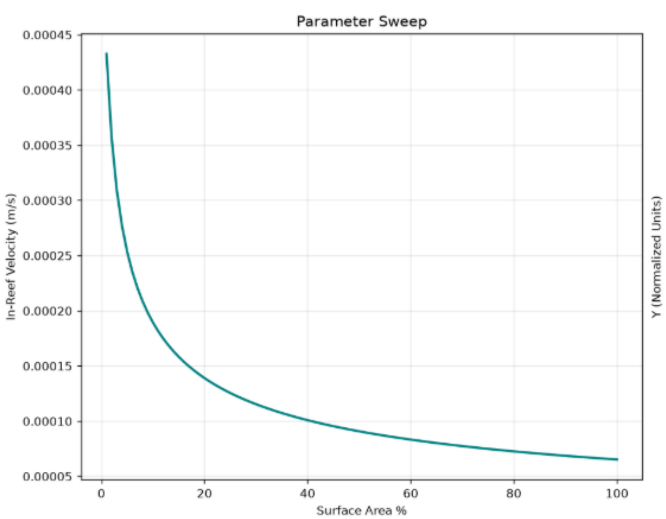

Fig. 3. Results of a parameter sweep across percent surface area. Percent surface area was used as a proxy for frontal area (λ_f) to assess the sensitivity of the system to this parameter.

APPENDIX B
PARAMETER EXTRACTION COMPARISON

TABLE I
WORKFLOW AND PARAMETER EXTRACTION COMPARISON.

Feature	**Synthetic Mesh**	**Real-World Mesh**
Data	Generated using 10,000 random Cartesian points which use a sinusoidal and Gaussian noise function to produce a structured but irregular terrain shape.	Loaded from a .glb file, and as such needs processing using trimesh.
Orientation	Not applicable as it was a consideration in the creation.	The orientation not being pre-defined allowed for a bounding-box logic to be applied where the shortest dimension became the vertical axis and the geometry was set and translated so the minimum elevation was the seafloor.
Height (h)	Calculated by subtracting the mean grid elevation from the arbitrary boundary: h = H - np.mean(grid_z).	Derived directly as the spatial mean value of the Digital Elevation Map: h_mean = np.mean(grid_z).
λ_f	Derived using spatial grid differences (np.diff).	Explored via a 100-step parameter sweep across the total surface area (mesh.area).
Slope (S)	Given an arbitrary constant value (0.001) to allow model implementation.	Given an arbitrary constant value (0.001) to allow model implementation.
Scaling	Coded directly into the mesh generation using metric units (L, W, H = 200).	Extracted from the raw file boundaries using mesh.extents.