Potential origin of the Stony coral tissue loss disease

Thomas Dobbelaere[1,*], Emmanuel Hanert[1,a]

[a] *Institute of Mechanics, Materials and Civil Engineering (IMMC), UCLouvain, Louvain-la-Neuve, Belgium*

Abstract

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetuer id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque

[*] Corresponding author

Email address: `thomas.dobbelaere@uclouvain.be` (Thomas Dobbelaere)

cursus luctus mauris.

Keywords: Stony coral tissue loss disease, sediments, Port of Miami, Coastal modeling,

1. Introduction

Coral diseases are a major threat to coral reef ecosystems and have led to significant declines in coral cover especially within the Caribbean region (Richardson et al., 1998; Sutherland et al., 2004; Aronson and Precht, 2001; Harvell et al., 2007; Brandt and McManus, 2009). One of the latest and the most damaging outbreak to date in Florida's Coral Reef (FCR) is stony coral tissue loss disease (SCTLD) (NOAA, 2018). First observed off the coast of Miami in 2014 by Precht et al. (2016), the disease has since spread through the entirety of FCR (Muller et al., 2020; Dobbelaere et al., in press 2022) and has been observed in several territories of the Caribbean (Kramer et al., 2019; Meiling et al., 2021; Estrada-Saldívar et al., 2021; Heres et al., 2021). Although the causative agent of the disease remains unknown, hydrodynamics are likely to play an important role in its propagation as both modeling studies and ex situ experiments show evidence of waterborne disease transmission (Aeby et al., 2019; Dobbelaere et al., 2020; Eaton et al., 2021; Meiling et al., 2021). Furthermore, recent studies showed evidence that sediments act as vector for the SCTLD (Rosales et al., 2020; Studivan et al., 2022).

SCTLD was first observed by Precht et al. (2016) near Virginia Key in September 2014, during the monitoring of the deepening of the Port of Miami (PoM) shipping channel, that took place between November 20, 2013 and March 16, 2015. This monitoring was performed twice-weekly at 26 monitoring stations established within the Miami-Dade County, making it one of the most complete datasets related to a dredging project (Gintert et al., 2019). While operating in a conventional way, dredged materials were pumped from the dredge to a spider barge and then transported to the US Environmental Protection Agency designated Ocean Dredge Material

Disposal Site (ODMDS) located 4.7 nautical miles offshore. However, the suction mechanism was turned off during non-conventional rock-chopping activities in order to pre-treat very hard rock contained in the Anastasia and Fort Thompson formations between December 2013 and May 2014. The Army Corps commissioned a report that provides a back-of-the-envelope estimating this practice could have resulted in up to 33 cm deposition over 874,121 m^2 of reef surrounding the outer entrance channel (Jocelyn Karazsia, *pers. comm.*). Additionally, several studies reported that the impact of the dredging was widespread (Miller et al., 2016), causing the death of $> 560,000$ corals within 0.5 km of the channel (Cunning et al., 2019) and producing sediment plumes covering up to 11 km^2 of coral area within 5-10 km of the dredge (Barnes et al., 2015).

Sediments released by dredging can affect the biological functions of corals in numerous ways (Erftemeijer et al., 2012; Jones et al., 2015). Increased turbidity caused by the suspended sediments reduces the light available to symbiotic zooxanthellae, leading to reduced coral cover and growth, while increased sedimentation can cause smothering or burial of coral polyps (Erftemeijer et al., 2012). Furthermore, sedimentation and turbidity can significantly reduce larval recruitment by inhibiting settlement and reducing larval survival in the water column (Jones et al., 2015). These effects are stronger with fine-grained sediments, as they cause a stronger light reduction (Fourney and Figueiredo, 2017). Additionally, fined-grained sediments such as silts have high nutrient contents, which can lead to an increased microbial activity, eventually causing anoxic conditions in the immediate vicinity of corals (Weber et al., 2012). As they release finer sediments over significantly longer periods than natural events such as hurricanes, dredging activities can thus be more harmful to corals and reef habitat compared to other types of sedimentation (Cunning et al., 2019).

Nonetheless, Gintert et al. (2019) argued that the reported coral mortality during the dredging project was dominated by the regional outbreak of

SCTLD. Further, the study suggested that the onset of the disease might have been linked to a leaking discharge pipe of the Miami Central District Municipal Wastewater Treatment Plant located off Virginia Key. However, as sediments can act as vector for SCTLD (Studivan et al., 2022), there is also a possibility that the causative agents of the disease was transported to the monitoring site of Virginia Key on sediments released by the dredging. This possibility can be evaluated using a bio-physical model simulating the transport of sediments produced during the dredging project. As coastal reef ecosystems are characterized by the complex topography of the coastline and the presence of islands, reefs and artificial structures, such a model would require high spatial resolution to accurately represent the transport of sediments at reef-scale. In this context, unstructured-mesh models are best suited, as they can easily adapt to the topography (Fringer et al., 2019) and can capture small-scale circulation features around reefs and islands (Lambrechts et al., 2008; Figueiredo et al., 2013).

The goal of this study is therefore to simulate the trajectories of the sediments released during the entirety of the deepening of the PoM shipping channel using a high-resolution hydrodynamic model coupled with a sediment transport model. Specifically, we will attempt to answer the following questions: (1) Which reefs were impacted by the dredging ? (2) Is the impact on these reefs consistent with the observed timing of the onset of SCTLD ?

2. Methods

The hydrodynamics over the entirety of FCR was modeled using the high resolution unstructured-mesh model SLIM[1], which has already been extensively validated in the area (Frys et al., 2020; Dobbelaere et al., 2020, in press 2022). SLIM uses an unstructured mesh whose resolution can be locally increased in order to accurately represent fine-scale flow features.

[1] https://www.slim-ocean.be

The mesh used in this study was built following the same methodology as Dobbelaere et al. (in press 2022), with a local refinement near PoM and in the Bay of Biscayne to achieve a resolution of 100 m in the vicinity of the dredged channel. It was made up of approximately 3.5×10^5 triangles and was generated with the seamsh[2] Python library, which is based on the the open-source mesh generator GMSH (Geuzaine and Remacle, 2009). The model was run between October 15, 2013 and September 26, 2014 to cover the whole dredging period prior to the first observation of SCTLD by Precht et al. (2016).

The transport of sediments released from the channel was then modeled using a Lagrangian particle tracking model, forced by SLIM velocity field. The sediment model is inspired by the Particle Transport Model (PTM), developed by the US Army Corps of Engineers (MacDonald et al., 2006). In this model, particles undergo a combination of horizontal and vertical motions. The vertical is mostly driven by gravity, with heavier particles sinking faster. Once sedimented, particles can be resuspended when shear stress exceed the critical Schields parameter, as parameterized by Soulsby et al. (1997). The horizontal motion of the suspended particles is dervued from the 2D model velocity by assuming a vertical log profile, following a quasi-3D approach. When sediment particles enter the near-bed zone, their horizontal velocity is greatly reduced and sediments are transported with the bedload.

As sediment dispersion is dependent on the grain size, we modeled the dispersal of five classes of sediments to represent to impact of fine- to coarse-grained particles: (*i*) 5-50 μm, (*ii*) 50-100 μm, (*iii*) 100-200 μm, (*iv*) 200-300 μm, and (*v*) 300-400 μm. We performed a different simulation for each class, with the grain size randomly drawn from a uniform distribution over the corresponding size range. The density of each sediment particle was derived from their size using the formula of Hamilton and Bachman

[2] `https://pypi.org/project/seamsh/`

(1982). Furthermore, all particles were differentiated based on the dredge that produced them. Five types of dredge were considered in our modeling study: (*a*) Texas cutterhead (TX), (*b*) non-conventional dredging, *i.e.* TX with suction mechanism turned off (NonConv), (*c*) Spider Barge (SB), (*d*) Terrapin Island hopper (TI), and (*e*) Dredge 55 clamshell (D55).

We had data about the date, location and type of all dredging operations performed during expansion of PoM. In the absence of information about the exact time of the dredging, sediment particles were released from the dredging location during a whole day at a rate of 80 particles/hour in the model. To account for the motion of spider barges between the dredging site and ODMDS, particles were released every 500 m along a straight line joining the dredging location to the ODMDS for every dredging operation labelled as SB.

TO DO: write about validation using presence-absence of plume ?

To evaluate the impact of dredging at the monitoring sites, we counted the number of sediment particles originating from each dredging that were transported within 500 m of all monitoring site. This number was then divided by the total number of sediment particles released by each type of dredge. Larger values of this indicator would suggest a greater impact of a given type of dredging at a given monitoring sites.

Furthermore, as previous studies showed evidence of waterborne transmission of SCTLD (Aeby et al., 2019; Dobbelaere et al., 2020; Eaton et al., 2021; Meiling et al., 2021), there is a possibility that the disease propagated to Virginia Key from unknown reefs affected prior to September 2014. To evaluate this possibility, we computed monthly disease connectivity matrices following the methodology of Dobbelaere et al. (2020) during our simulated period. These connectivity matrices can be interpreted as large graphs whose vertices are reefs and whose edges represent disease connectivity pathways. Evaluating the possibility of disease propagation from one reef to another is therefore equivalent to evaluating the presence of paths connecting these two reefs in the network. As computing all possible paths is not computationally tractable, we limited ourselves to the computation of shortest paths from any given reefs to the Virginia Key monitoring site. This was performed using the function `get_all_shortest_paths` of the Python `python-igraph` package (Csardi et al., 2006). Such function requires the definition of a weight w_{ij} for the edge connecting reef i to reef j. We chose $w_{ij} = 1 - \tilde{C}_{ij}$, where $\tilde{C}_{ij}$ is the probability of disease propagation from reef i to reef j, so that "shorter" edges of the networks (*i.e.* connectivity pathways with smaller weights) correspond to connections with larger disease propagation probability. The probability of a given path was then defined as the mean connection probability of the edges composing this path.

3. Results

4. Discussion

5. Conclusion

References

Aeby, G., Ushijima, B., Campbell, J.E., Jones, S., Williams, G., Meyer, J.L., Hase, C., Paul, V., 2019. Pathogenesis of a tissue loss disease affecting multiple species of corals along the Florida Reef Tract. Frontiers in Marine Science 6, 678.

Aronson, R.B., Precht, W.m.F., 2001. White-band disease and the changing face of Caribbean coral reefs. The ecology and etiology of newly emerging marine diseases , 25–38.

Barnes, B.B., Hu, C., Kovach, C., Silverstein, R.N., 2015. Sediment plumes induced by the Port of Miami dredging: Analysis and interpretation using Landsat and MODIS data. Remote Sensing of Environment 170, 328–339.

Brandt, M.E., McManus, J.W., 2009. Dynamics and impact of the coral disease white plague: insights from a simulation model. Diseases of aquatic organisms 87, 117–133.

Csardi, G., Nepusz, T., et al., 2006. The igraph software package for complex network research. InterJournal, complex systems 1695, 1–9.

Cunning, R., Silverstein, R.N., Barnes, B.B., Baker, A.C., 2019. Extensive coral mortality and critical habitat loss following dredging and their association with remotely-sensed sediment plumes. Marine pollution bulletin 145, 185–199.

Dobbelaere, T., Muller, E.M., Gramer, L.J., Holstein, D.M., Hanert, E., 2020. Coupled epidemio-hydrodynamic modeling to understand the spread of a deadly coral disease in Florida. Frontiers in Marine Science 7, 1016.

Dobbelaere, T., Muller, E.M., Gramer, L.J., Holstein, D.M., Hanert, E., in press 2022. Connecting the dots: Transmission of stony coral tissue loss disease from the marquesas to the Dry Tortugas. Frontiers in Marine Science doi:10.3389/fmars.2022.778938.

Eaton, K.R., Landsberg, J.H., Kiryu, Y., Peters, E.C., Muller, E.M., 2021. Measuring stony coral tissue loss disease induction and lesion progression within two intermediately susceptible species, Montastraea cavernosa and Orbicella faveolata. Frontiers in Marine Science , 1287.

Erftemeijer, P.L., Riegl, B., Hoeksema, B.W., Todd, P.A., 2012. Environmental impacts of dredging and other sediment disturbances on corals: a review. Marine pollution bulletin 64, 1737–1765.

Estrada-Saldívar, N., Quiroga-García, B.A., Pérez-Cervantes, E., Rivera-Garibay, O.O., Alvarez-Filip, L., 2021. Effects of the stony coral tissue loss disease outbreak on coral communities and the benthic composition of cozumel reefs. Frontiers in Marine Science 8, 306.

Figueiredo, J., Baird, A.H., Connolly, S.R., 2013. Synthesizing larval competence dynamics and reef-scale retention reveals a high potential for self-recruitment in corals. Ecology 94, 650–659.

Fourney, F., Figueiredo, J., 2017. Additive negative effects of anthropogenic sedimentation and warming on the survival of coral recruits. Scientific reports 7, 1–8.

Fringer, O.B., Dawson, C.N., He, R., Ralston, D.K., Zhang, Y.J., 2019. The future of coastal and estuarine modeling: Findings from a workshop. Ocean Modelling 143, 101458.

Frys, C., Saint-Amand, A., Le Hénaff, M., Figueiredo, J., Kuba, A., Walker, B., Lambrechts, J., Vallaeys, V., Vincent, D., Hanert, E., 2020. Fine-scale coral connectivity pathways in the Florida Reef Tract: Implications for conservation and restoration. Frontiers in Marine Science 7, 312.

Geuzaine, C., Remacle, J.F., 2009. Gmsh: A 3-D finite element mesh generator with built-in pre-and post-processing facilities. International journal for numerical methods in engineering 79, 1309–1331.

Gintert, B.E., Precht, W.F., Fura, R., Rogers, K., Rice, M., Precht, L.L., D'Alessandro, M., Croop, J., Vilmar, C., Robbart, M.L., 2019. Regional coral disease outbreak overwhelms impacts from a local dredge project. Environmental monitoring and assessment 191, 1–39.

Hamilton, E.L., Bachman, R.T., 1982. Sound velocity and related properties of marine sediments. The Journal of the Acoustical Society of America 72, 1891–1904.

Harvell, D., Jordán-Dahlgren, E., Merkel, S., Rosenberg, E., Raymundo, L., Smith, G., Weil, E., Willis, B., 2007. Coral disease, environmental drivers, and the balance between coral and microbial associates. Oceanography 20, 172–195.

Heres, M.M., Farmer, B.H., Elmer, F., Hertler, H., 2021. Ecological consequences of stony coral tissue loss disease in the turks and caicos islands. Coral Reefs 40, 609–624.

Jones, R., Ricardo, G., Negri, A., 2015. Effects of sediments on the reproductive cycle of corals. Marine Pollution Bulletin 100, 13–33.

Kramer, P., Roth, L., Lang, J., 2019. Map of stony coral tissue loss disease outbreak in the Caribbean. URL: `www.agrra.org`. ArcGis Online. (accessed June 12, 2020).

Lambrechts, J., Hanert, E., Deleersnijder, E., Bernard, P.E., Legat, V., Remacle, J.F., Wolanski, E., 2008. A multi-scale model of the hydrodynamics of the whole Great Barrier Reef. Estuarine, Coastal and Shelf Science 79, 143–151.

MacDonald, N.J., Davies, M.H., Zundel, A.K., Howlett, J.D., Demirbilek, Z., Gailani, J.Z., Lackey, T.C., Smith, J., 2006. PTM: particle tracking model. Report 1: Model theory, implementation, and example applications. Technical Report. Engineer Research And Development Center Vicksburg MS Coastal And Hydraulics Lab.

Meiling, S.S., Muller, E.M., Lasseigne, D., Rossin, A., Veglia, A.J., MacKnight, N., Dimos, B., Huntley, N., Correa, A., Smith, T.B., et al., 2021. Variable species responses to experimental stony coral tissue loss disease (SCTLD) exposure. Frontiers in Marine Science 8, 464.

Miller, M.W., Karazsia, J., Groves, C.E., Griffin, S., Moore, T., Wilber, P., Gregg, K., 2016. Detecting sedimentation impacts to coral reefs resulting from dredging the Port of Miami, Florida USA. PeerJ 4, e2711.

Muller, E.M., Sartor, C., Alcaraz, N.I., van Woesik, R., 2020. Spatial epidemiology of the stony-coral-tissue-loss disease in Florida. Frontiers in Marine Science 7, 163.

NOAA, 2018. Stony Coral Tissue Loss Disease Case Definition. URL: https://nmsfloridakeys.blob.core.windows.net/floridakeys-prod/media/docs/20181002-stony-coral-tissue-loss-disease-case-definition.pdf. Accesssed on June 4, 2020.

Precht, W.F., Gintert, B.E., Robbart, M.L., Fura, R., Van Woesik, R., 2016. Unprecedented disease-related coral mortality in Southeastern Florida. Scientific reports 6, 1–11.

Richardson, L.L., Goldberg, W.M., Carlton, R.G., Halas, J.C., 1998. Coral disease outbreak in the Florida Keys: plague type II. Revista de Biología tropical , 187–198.

Rosales, S.M., Clark, A.S., Huebner, L.K., Ruzicka, R.R., Muller, E., 2020. Rhodobacterales and Rhizobiales are associated with stony coral tissue loss disease and its suspected sources of transmission. Frontiers in Microbiology 11, 681.

Soulsby, R., Whitehouse, R., et al., 1997. Threshold of sediment motion in coastal environments, in: Pacific Coasts and Ports'97. Proceedings, pp. 149–154.

Studivan, M.S., Rossin, A.M., Rubin, E., Soderberg, N., Holstein, D.M., Enochs, I.C., 2022. Reef sediments can act as a stony coral tissue loss disease vector. Frontiers in Marine Science , 2046.

Sutherland, K.P., Porter, J.W., Torres, C., 2004. Disease and immunity in Caribbean and Indo-Pacific zooxanthellate corals. Marine ecology progress series 266, 273–302.

Weber, M., De Beer, D., Lott, C., Polerecky, L., Kohls, K., Abed, R.M., Ferdelman, T.G., Fabricius, K.E., 2012. Mechanisms of damage to corals exposed to sedimentation. Proceedings of the National Academy of Sciences 109, E1558–E1567.