Technical Advisory Committee

Living Resources for

Long Island Sound Integrated Model

FINAL REPORT

Submitted to:

New York City Department of Environmental Protection
Bureau of Environmental Planning and Analysis
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December 23, 2022 (V1)

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Table of Contents

List of Tables

List of Figures

1. Background

Following the massive anoxic event and the devastation of fishery resources off the NJ coast in the summer of 1976 (Swanson and Sindermanm, 1979), the persistent occurrence of coastal hypoxia was recognized by academic researchers and federal regulators as a major worldwide water quality management issue. (Diaz and Rosenberg, 2008; 2011; Rabelais et al., 2010; Altieri & Gedan, 2015). Federal agencies, including EPA, USGS and NOAA, started and began to standup long-term programs to study and mitigate hypoxic conditions in various estuaries such as the Gulf of Mexico (EPA, 2022; NOAA, 2022a) and Chesapeake Bay (NOAA, 2022b). As noted by Diaz and Rosenberg (2011), the environmental and economic consequences of hypoxia in coastal systems can be substantive. As a consequence of the anoxic event of 1976 in the New York Bight, total estimated losses to the commercial fishery were $569 million (based on late-1970s dollars). The total estimate of $569 million accounts for (a) actual 1976 resource losses ($70 million) and (b) future resource losses ($499 million) until recruitment replenishes the affected fishery stocks. Losses to surf clam stocks ($62 million) accounted for the largest share of the total actual fishery loss of $70 million from the 1976 anoxic event while actual losses to the recreational fishery accounted for $3.7 million (see Table 14-7 in Figley et al., 1979).

1.1 Hypoxia in Long Island Sound

Recurrent hypoxic conditions during summer stratified conditions in the Western Basin of LI Sound were first monitored on an annual basis beginning in 1991 in response to the identification of hypoxia as a significant water quality issue (CTDEP, 2000). EPA initiated the Long Island Sound Study (LISS) in 1985 as a State-Federal partnership to address alternative strategies for control of pollutant loading to reduce the occurrence and persistence of hypoxic conditions in Western Long Island Sound (USEPA, 2022a). Figure 1-1 shows the spatial pattern of hypoxic conditions in LI Sound from west to east based on aggregation and analysis of annual summer survey data sets from 1994-2021 (Dykes, Powers and Tedesco, 2021).

The frequency of occurrence of bottom water hypoxia shown in the map is based on pooling DO data collected by Connecticut Dept. Energy and Environmental Protection (CTDEEP) and Interstate Environmental Commission (IEC) during annual summer surveys (June – September) from 1994-2021 (Dykes, Powers and Tedesco, 2021). Bottom water is defined by IEC's (2018) EPA-approved QAPP as samples collected approximately 1 meter above the bottom. Bottom water is defined by CTDEEP's (2017) EPA-approved QAPP as monthly survey samples collected 3 – 5 meters above the sediment bed. Bottom water DO measurements, collected during summer surveys from 1994 – 2021, are pooled for each CTDEEP and IEC station. The frequency of hypoxia is computed and mapped for each station as the percentage of samples collected from 1994 – 2021 that are characterized by DO levels less than 3.0 mg/L. Based on more than two decades of summer surveys, the map shows a clear pattern of persistent hypoxic conditions in Western LI Sound and a pattern of decreasing hypoxia from west to east in LI Sound. The year to year variability of the maximum areal extent and duration of hypoxic conditions in LI Sound is shown elsewhere in this section (see Figure 1-4).

Under the LISS, planning efforts by EPA and the States were focused on control of external loading of nitrogen and the cause-effect linkage between nutrient loading from coastal watersheds with nutrient enrichment, phytoplankton production, seasonal stratification and the annual occurrence of hypoxic conditions in Western LI Sound. Controllable sources of nutrient loading included runoff from coastal watersheds, wastewater discharges and urban stormwater including combined sewer overflows (CSO). Beginning in 1988 (see NOAA, 1994), watershed, hydrodynamic and water quality models were developed by NOAA and HydroQual, Inc. for LI Sound and adjacent estuarine waters to support water quality management planning efforts by EPA and State-local environmental agencies (New York, Connecticut and New York City (US EPA, 2022a). The outcome of the water quality management planning efforts by EPA led to development of the 2001 Nitrogen TMDL that established point and nonpoint source nitrogen reduction targets within LI Sound (NYSDEC and CTDEP, 2000).

1.2 Long Island Sound Hydrodynamic and Water Quality Models

LIS 1.0 (Steady-State), LIS 2.0 (2D) and LIS 3.0 (3D). HydroQual developed an increasingly complex series of models of LI Sound that included 2D steady-state (LIS 1.0) and 2D time-variable (LIS 2.0). The 3D time-variable model (LIS 3.0) was based on linkage of a hydrodynamic model (ECOM) with a water quality model (RCA) (HydroQual, 1996). The LIS 3.0 model framework was then used to support development of the TMDL for coastal nitrogen loading to Long Island Sound (NYSDEC and CTDEP, 2000) (Source: UCONN, System-Wide Eutrophication Model- History https://swem.uconn.edu/#). The TMDL was then approved by EPA in 2001 (USEPA, 2022a).

System-Wide Eutrophication Model (SWEM). Beginning in the mid-1990's, funding was provided by NYCDEP to support development of a new "system-wide" model with new field data collected from September 1994 through September 1995 to support model calibration. The spatial domain of the LIS 3.0 model was expanded from LI Sound only to include NY Harbor and the New York Bight continental shelf (Figure 1-2). The domain was expanded for two reasons: (1) address model limitations for representation of open water boundary conditions identified by peer-review and (2) provide a system-wide LIS-NY Harbor-NY Bight model that was needed by NYCDEP to support evaluations of upgrades to NYC municipal wastewater facilities and assessments of the potential impact of relocating NYC municipal wastewater discharges from the East River to ocean outfalls in Nassau County on the south shore of Long Island.

Following completion of SWEM in 2001, the operational model was used to support a number of assessments including re-evaluation of the LI Sound nitrogen TMDL and technical support for the nitrogen trading program of Connecticut Dept. Environmental Protection (CTDEP). The SWEM was also used by NYCDEP to develop nested models of local-scale embayments (e.g., Jamaica Bay) and tidal rivers (e.g., Newtown Creek) to support development of Long-Term Control Plans for CSO strategies and wastewater upgrades (see HydroQual, 2001). Peer reviews documented by O'Donnell et al. (2010; 2014) identified technical problems with SWEM representations of vertical mixing and algal kinetics that affected simulation results for dissolved oxygen. (Source: UCONN, System-Wide Eutrophication Model- History https://swem.uconn.edu/#). In addition to water quality management planning studies, SWEM was also used to support the linkage of ECOM-RCA with living resources models to support analyses of ecological and economic benefits provided by living resources such as oysters (Miller and Wands, 2009; Bricker et al., 2015, 2018) and seaweed (Miller and Wands, 2009).

1.3 EPA 2015 "Nex-Gen" Strategy

As shown in Figure 1-3, combined wastewater loading of Total Nitrogen (TN) to LI Sound from New York and Connecticut began a gradual decline in 1997 that continued for ~ 20 years to 2017 (USEPA, 2022c). By 2014, wastewater TN reductions by Connecticut and the investment in Biological Nutrient Removal at NYCDEP wastewater treatment facilities achieved, and surpassed, the TN target loading established for 2017 as the goal by the TMDL (USEPA, 2022c).

Annual surveys of hypoxia in LI Sound have been reported by CTDEP, the IEC and the LISS since the early 1990's. Each year the annual hypoxia report summarizes data collected in previous years to show the west to east spatial pattern of hypoxia in LI Sound and long-term trends in area (square miles) and duration (days) of hypoxic conditions within LI Sound. Figure 1-1 shows the composite spatial pattern from 1994-2021 and Figure 1-4 shows the trend in hypoxic conditions from 1987 to 2021 (Dykes, Powers and Tedesco, 2021). As can be seen, the 5-year rolling average trend for hypoxic area has been gradually decreasing each year since 2007.

"*Despite the progress*" required to achieve 52% reduction in TN loading to LI Sound, EPA informed the States of NH, MA, VT, CT and NY that "*there is more to do*" (Spalding and Enck, 2015). EPA's "Nex-Gen Strategy" (USEPA, 2015) expanded the focus of water quality management efforts well beyond the consideration of hypoxia alone to include assessments of the impact of nutrient loading and nutrient enrichment on living resources in the open waters and coastal watersheds of LI Sound.

1.4 SWEM Peer Review and Recommendations

University of Connecticut Dept. of Marine Sciences researchers (O'Donnell et al., 2010, 2014) performed a detailed independent evaluation of the SWEM model with the original data collected in 1988-1989 and 1994-1995 as well as new data sets collected during 1999 - 2002. O'Donnell et al. (2010) identified and documented technical problems with the SWEM results for dissolved oxygen that were related to vertical mixing and parameterization of phytoplankton production and respiration processes. O'Donnell et al. (2014) concluded that the RCA water quality model, as configured for the SWEM grid resolution of LI Sound (see Figure 1-2), was unable to accurately represent observed summer distributions of near bottom DO under summer stratified conditions in western Long Island Sound.

The re-calibration efforts of O'Donnell et al (2014) were not considered sufficient enough to warrant recommendations to continue using SWEM as a planning tool to support TMDL evaluations for LI Sound. O'Donnell et al. (2014) recommended that a much finer-scale horizontal resolution grid for LI Sound be developed to reduce the effect of numerical dispersion on vertical mixing and to improve simulation of cross-Sound (lateral) transport of water as a hydrodynamic response to wind forcing. Improvements in grid resolution and the hydrodynamic model, would in turn, be expected to improve model-data agreement for near bottom DO, including hypoxic conditions, under summer stratified conditions.

Based on peer review findings and recommendations of O'Donnell and his colleagues, EPA concluded that grant funding needed to be provided to DEP to develop a new and improved system-wide hydrodynamic and water quality model for LI Sound. The new system-wide, scientifically defensible model framework would be used to support improved water quality management planning efforts related to the LI Sound TMDL for nitrogen loading. Consistent with EPA's "Nex-Gen" Strategy described above, the new hydrodynamic and water quality model framework would also provide DEP the opportunity to design an Integrated Model Framework (IMF) to link the effects of external loading, eutrophication and nutrient enrichment with ecological models to represent living resources. Section 2 presents an overview of the components of the IMF and approaches to be considered for linkage of living resource models with hydrodynamic and water quality models.

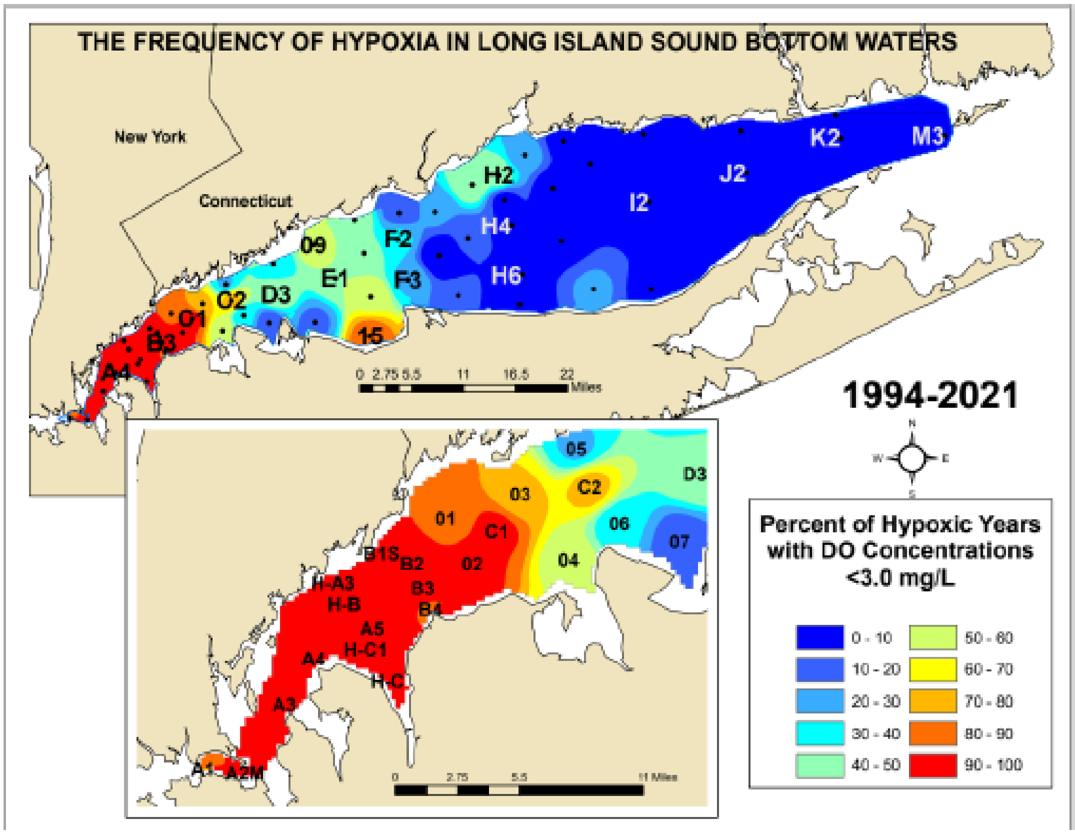

Figure 1-1 Frequency of Hypoxia in Long Island Sound Bottom Waters from 1994-2021 (Source: Dykes, Powers and Tedesco, 2021)

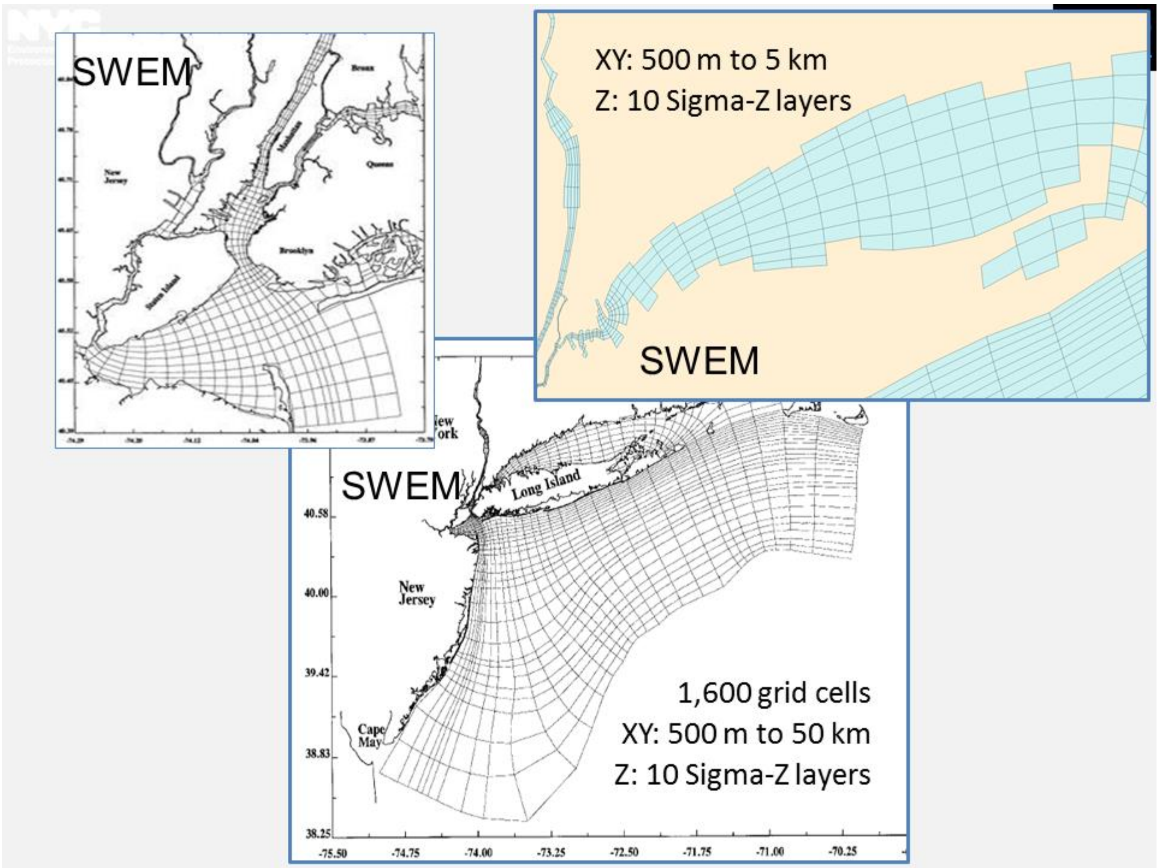

Figure 1-2 System-Wide Eutrophication Model Grid for LI Sound, NY Harbor and NY Bight. Sources: Blumberg et al. (1999) and Miller (2010)

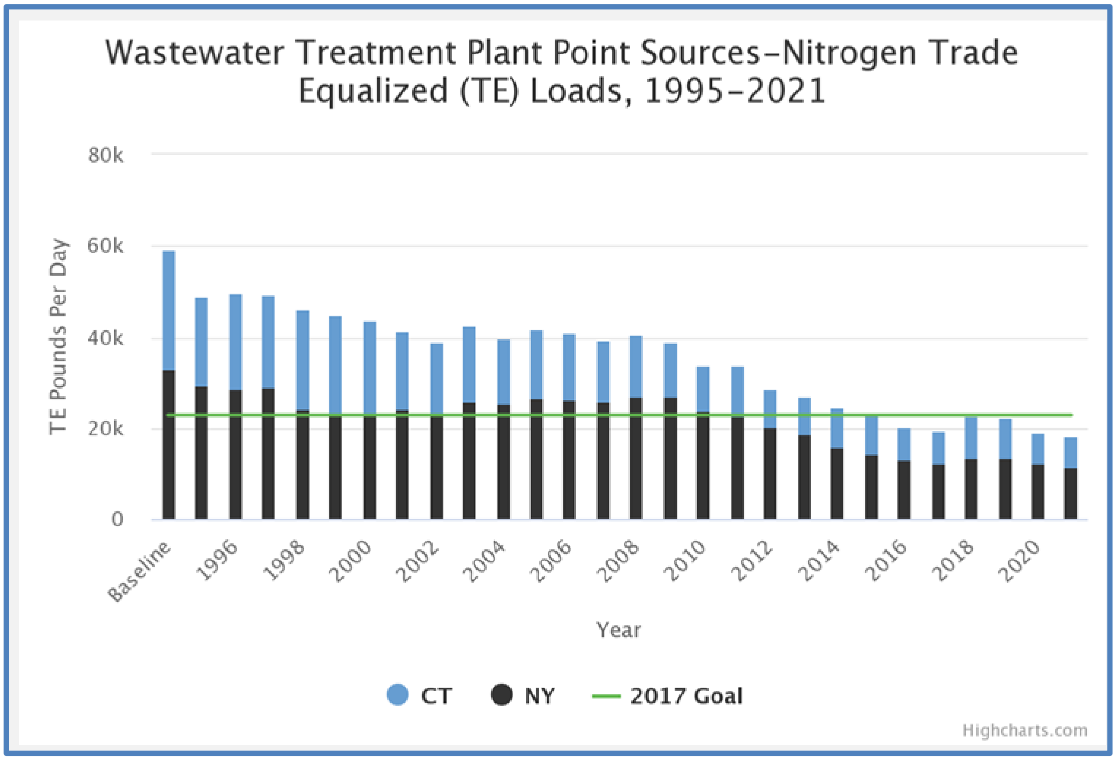

Figure 1-3 Trends in Wastewater Effluent Loading of Total Nitrogen:1995-2021. Blue bars represent CT loads and black bars represent NY loads. The green line shows the 2017 goal for TN loading (Source: EPA, 2022c)

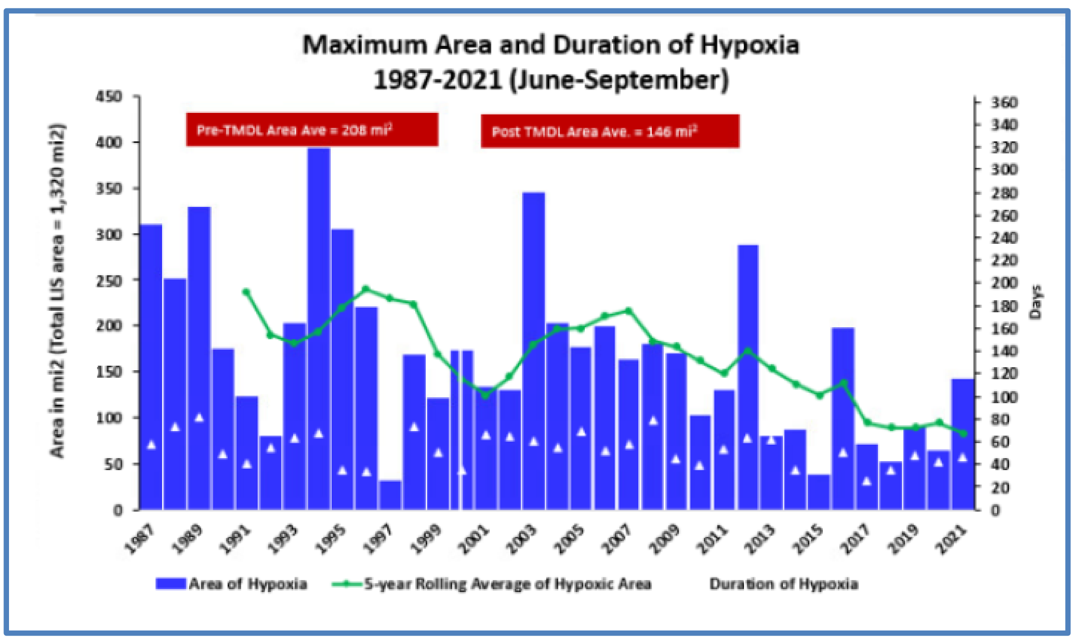

Figure 1-4 Maximum area and duration of hypoxia. Blue bars represent area of hypoxic conditions (as sq-miles), white triangles represent duration of hypoxic conditions (as days) and the green line is the 5-year rolling average of hypoxic area (Source: Dykes, Powers and Tedesco, 2021)

1.5 Section 1 References

Altieri, A.H. and Gedan, K.B. (2015). Climate change and dead zones. *Global Change Biology* 21, 1395 – 1406.

Blumberg, Alan F., L.A. Khan, and J.P. St. John. (1999). Three-Dimensional Hydrodynamic Model of New York Harbor Region. ASCE Journal of Hydraulic Engineering, Vol. 125, No. 8. Paper No. 18077.

Bricker, S.B., J. Ferreira, C. Zhu, J. Rose, E. Galimany, G. Wikfors, C. Saurel, R. Landeck Miller, J. Wands, P. Trowbridge, R. Grizzle, K. Wellman, R. Rheault, J. Steinberg, A. Jacob, E. Davenport, S. Ayvazian, M. Chintala, and M. Tedesco. 2015. An Ecosystem Services Assessment using bioextraction technologies for removal of nitrogen and other substances in Long Island Sound and the Great Bay/Piscataqua Region Estuaries. NCCOS Coastal Ocean Program Decision Analysis Series No. 194. National Oceanic and Atmospheric Administration, National Centers for Coastal Ocean Science, Silver Spring, MD and United States Environmental Protection Agency, Office of Research and Development, Atlantic Ecology Division, Narragansett, RI. 154 pp + 3 appendices.

Bricker SB, Ferreira JG, Zhu C, Rose JM, Galimany E, Wikfors GH, Saurel C, Miller RL, Wands J, Trowbridge P, Grizzle RE, Wellman K, Rheault R, Steinberg J, Jacob AP, Davenport ED, Ayvazian S, Chintala M, and Tedesco MA 2018 The role of shellfish aquaculture in reduction of eutrophication in an urban estuary. Environmental Science & Technology 52 (1): 173–183. [PubMed: 28994282]

CTDEP (2000) Long Island Sound Ambient Water Quality Monitoring Program: Summer Hypoxia Monitoring Survey 1991-1998 Data Review. Report prepared by Connecticut Department of Environmental Protection, Hartford, CT, September.

CTDEEP (2017) Quality Assurance Project Plan: Long island Sound Ambient Water Quality Monitoring Program. Prepared by CTDEEP, Bureau of Water Protection and Land Reuse, Hartford, CT, Rev. 05092017, Version 1.0, EPA Grant Nos. LI00A00372, RFA number 17069.

Diaz, R. J., & Rosenberg, R. (2008). Spreading Dead Zones and Consequences for Marine Ecosystems. *Science*, *321*(5891), 926–929. http://www.jstor.org/stable/20144596

Diaz, R.J. and R. Rosenberg (2011) Introduction to Environmental and Economic Consequences of Hypoxia, International Journal of Water Resources Development, 27:1,71-82, DOI: 10.1080/07900627.2010.531379

Dykes, K., E. Powers and M. Tedesco (2021) 2021 Long Island Sound Hypoxia Season Review. Annual report prepared by Connecticut Department of Energy and Environmental Protection, Hartford, CT; Interstate Environmental Commission, Staten Island, NY; and US EPA Long Island Sound Office, Stamford, CT.

Figley, W., Pyle, B. and Halgren, B. (1979) Socioeconomic impacts, in: Swanson, R.L and Sindermann, C.J. (eds.) (1979) Oxygen Depletion and Associated Benthic Mortalities in New York Bight, 1976. NOAA Prof. Paper 11, U.S. Dept. Commerce, National Oceanic and Atmospheric Administration (NOAA), Rockville, MD, pp. 315-322.

HydroQual (1996) Water Quality Modeling Analysis of Hypoxia in Long Island Sound using LIS 3.0. Prepared for the Management Committee of the Long Island Sound Study and the New England Interstate Water Pollution Control Commission. HydroQual, Inc., Mahwah, NJ

HydroQual (2001) Newton Creek Water Pollution Control Project East River Water Quality Plan, Task 10.0 System Wide Eutrophication Model (SWEM), Subtask 10.4 Calibrate SWEM Water Quality, Subtask 10.6 Validate SWEM Water Quality. HydroQual, Inc., Mahwah, NJ, April, *G-176-SWEM.pdf*

IEC (2018) Quality Assurance Project Plan: Ambient Water Quality Monitoring in the Far Western Long Island Sound. Prepared by Interstate Environmental Commission (IEC), Staten Island, NY, May 21, 2018, Version 5.0, EPA Grant Nos. LI00A00372, RFA number 18077.

Miller, R. and J. Wands (2009) Applying the System-Wide Eutrophication Model (SWEM) for a preliminary quantitative evaluation of biomass harvesting as a nutrient control strategy for Long Island Sound, In: Rose et al. (2010), Presented at Nutrient Bioextraction Workshop https://longislandsoundstudy.net/our-vision-and-plan/clean-waters-and-healthy-watersheds/nutrient-bioextraction-overview/nutrient-bioextraction/

Miller, R. (2010) System Wide Eutrophication Model (SWEM) – Case Study: 20 Years of Hypoxia Management in the NY/NJ Harbor-NY Bight-Long Island Sound System. Sea Grant, New York Bight Workshop. July 7, 2010, http://longislandsoundstudy.net/wp-content/uploads/2010/06/SWEMbiohrvstrprtv2_12_04_09.pdf

O'Donnell, J., G. McCardell, T. Fake, and H. Dam. (2010). Final Report: Simulation of Long Island Sound with the System-Wide Eutrophication Model (SWEM): Inter-annual Variability and Sensitivity. 10.13140/RG.2.1.4796.0083, May.

O'Donnell, J., J.J. Fitzpatrick, G. McCardell, T. Fake, and R. Horowitz. (2014). Final Report: The Development of a Community Model of Nutrient Transport and Cycling for Long Island Sound. New England Interstate Water Pollution Control Commission and the Long Island Sound Study, September.

NOAA. (1994). Long Island Sound Oceanography Project. Summary Report, Volume 1: Application and Documentation of the Long Island Sound Three-Dimensional Circulation Model. NOAA Technical Report NOS OES 003, NOAA National Ocean Service, Silver Spring, MD.

NOAA (2022a) Gulf of Mexico Hypoxia, https://www.ncei.noaa.gov/products/gulf-mexico-hypoxia-watch, Retrieved October 30, 2022

NOAA (2022b) Chesapeake Bay Hypoxia, https://coastalscience.noaa.gov/news/modeling-shows-nitrogen-reductions-have-decreased-hypoxia-in-chesapeake-bay/), accessed Oct-30-2022

NYSDEC and CTDEP (2000) A Total Maximum Daily Load Analysis to Achieve Water Quality Standards for Dissolved Oxygen in Long Island Sound, Prepared by New York State Dept. of Environmental Conservation, Albany, NY and Connecticut Dept. of Environmental Protection, Hartford, CT, December.

Rabalais, N. R. J. Dıaz, L. A. Levin, R. E. Turner, D. Gilbert, and J. Zhang (2010) Dynamics and distribution of natural and human-caused hypoxia, Biogeosciences 7: 585-619

Rose J.M., M. Tedesco, G.H. Wikfors, C. Yarish (2010). International Workshop on Bioextractive Technologies for Nutrient Remediation Summary Report. US Dept Commerce, Northeast Fish Sci Cent

Ref Doc. 10-19; 12 p. Available from: National Marine Fisheries Service, 166 Water Street, Woods Hole, MA 02543-1026, or online at http://www.nefsc.noaa.gov/nefsc/publications/

Spalding and Enck (2015) Memorandum to Commissioners of State Environmental agencies for NH, VT, MA, CT and NY from H Curtis Spalding, EPA Regional Administrator (Region 1) and Judith A. Enck, EPA Regional Administrator (Region 2), December 23, 2015. https://longislandsoundstudy.net/wp-content/uploads/2016/02/LIS-Nitrogen-Strategy-Cover-Letter-final-12-23-15.pdf

Swanson, R.L and C.J. Sindermann (eds.) (1979) Oxygen Depletion and Associated Benthic Mortalities in New York Bight, 1976. NOAA Prof. Paper 11, U.S. Dept. Commerce, National Oceanic and Atmospheric Administration (NOAA), Rockville, MD, 345 pp.

University of Connecticut, System-Wide Eutrophication Model- History, https://swem.uconn.edu/#, Retrieved September 30, 2022

USEPA (1998) Long Island Sound Study Phase III Actions for Hypoxia Management, EPA 902-R-98-002, US Environmental Protection Agency,

USEPA (2015) Evolving the Long Island Sound Nitrogen Reduction Strategy, US Environmental Protection Agency, December 2015. US Environmental Protection Agency, Region 1 (Boston, MA) and Region 2 (New York City, NY). December. https://longislandsoundstudy.net/wp-content/uploads/2016/02/LIS-Nitrogen-Strategy-Enclosures-12-23-15-1.pdf

USEPA (2022a) Gulf of Mexico Hypoxia https://www.epa.gov/ms-htf, Retrieved October 30, 2022

2. Integrated Modeling Framework

In FY17, $6.0 million in cost-share funding was secured from EPA and NYC Department of Environmental Protection (DEP) to support the effort required to update and improve a system-wide hydrodynamic and water quality model for LI Sound. The updated modeling effort was needed to ensure that any future required nutrient mitigation efforts are based on the best available current data and sound/defensible science, and to enable stakeholders to model the potential impacts of future conditions on nutrient management strategies such as may be associated with climate change or watershed-based point and nonpoint source control strategies.

In 2020, DEP initiated a project to develop an updated comprehensive hydrodynamic and water quality model for Long Island (LIS). The DEP Long Island Sound Hydrodynamic and Water Quality Modeling Support project (LIS-HWQMS) includes the development of updated hydrodynamic and water quality models (HWQMS) of LI Sound. The LIS-HWQMS, currently under development by HDR, provides the physical and biogeochemical components of the overall Integrated Model Framework (IMF) to ensure that physical, biogeochemical, and living resource sub-models provide science-based representations of how these sub-models drive circulation and mixing, biogeochemical interactions that control dissolved oxygen (especially the onset and persistence of hypoxia), nutrient cycling, eutrophication, water clarity, ecological processes and living resources in estuarine and coastal waters.

The IMF will support assessment of management strategies for a range of spatial scales including (a) system-wide (LI Sound, New York Bight, New York Harbor), (b) regional (LI Sound), and (c) local embayments and tidal river/estuaries (e.g., Port Jefferson Harbor, NY; Niantic River/estuary, CT). The IMF will be developed in a modular fashion over a period of several years to account for the linkage between watershed loading, hydrodynamics, water quality and living resources. It is anticipated that the IMF will provide a state-of-the-art modeling framework to support science-based assessments and decision-making for investments in management strategies for the next decade (or longer) by DEP, EPA, and State agencies (NYSDEC, CTDEEP, NJDEP). Watershed loading and nutrient management strategies will be evaluated with the IMF to achieve compliance with regulatory and policy goals as established by EPA's NexGen Strategy (EPA, 2015). The IMF, developed with public funding from EPA and DEP, must be developed using open-source model software so that the IMF will be accessible to all Stakeholders including State, federal, local agencies; the academic community; environmental advocacy groups; and regulated entities.

2.1 Components of Integrated Modeling Framework (IMF)

The major components of the IMF include: (a) watershed and atmospheric deposition, (b) hydrodynamics, (c) water quality, and (d) living resources. Brief descriptions of the non-living resources component of the IMF are presented below. Species groups considered for the living resources component of the IMF are described in Section 5.

Watershed and Atmospheric Deposition. Watershed loading represents flow and mass loading from (a) coastal rivers, (b) nonpoint source distributed runoff, (c) municipal and industrial wastewater treatment facilities, (d) stormwater (MS4) outlets, (e) CSO outfalls, and (f) groundwater inputs. Watershed loading also includes atmospheric deposition of nutrients over the watershed landscape and over the open waters of LI Sound, New York Harbor and the New York Bight.

Hydrodynamics. The open-source Regional Ocean Model (ROMS) was selected as the hydrodynamic model to support development of the physical transport component of the LIS-HWQMS (HDR, 2021). ROMS is a state-of-the-art ocean model widely used and supported by the scientific community for a diverse range of applications including biogeochemical models (Fennel et al., 2006).

The computational grid of ROMS is based on horizontal curvilinear coordinates and the sigma-stretch scheme in the vertical (https://www.myroms.org/) and the hydrodynamic model represents the effects of shoreline and bathymetry, freshwater forcing from coastal rivers and other watershed-related point source and nonpoint source flow inputs, atmospheric forcing (e.g., incident solar radiation), meteorological forcing and open ocean tidal forcing along the open water boundary of the continental shelf. ROMS is an advanced hydrodynamic model that accounts for (a) barotropic (pressure gradient) and (b) baroclinic (density gradient) components of 3D transport processes and offers (c) several optional turbulent closure schemes to model vertical mixing processes. State variables of the ROMS hydrodynamic model are water surface elevation, velocity, water temperature and salinity. ROMS can also be configured to internally couple biogeochemical, bio-optical applications and suspended sediment and sediment transport processes with the hydrodynamic model. The ROMS curvilinear grid for the LIS-HWQMS is shown for the system-wide domain in Figure 2-1 with details of the LI Sound portion of the grid shown in Figure 2-2.

Water Quality. The RCA model has been selected as the water quality model to support development of the biogeochemical component of the LIS-HWQMS (HDR, 2021). RCA has a long history of water quality model applications in the New York – New Jersey region including the System Wide Eutrophication Model (SWEM) for LI Sound (Hydro Qual, 2001a, 2001b, 2001c). State variables of the RCA water quality model application for the LIS-HWQMS project include dissolved oxygen, three functional groups of phytoplankton, organic and inorganic forms of nutrients (N, P, Si), dissolved and particulate forms of organic carbon and Total Suspended Solids (TSS). State variables for organic carbon are used to derive CBOD as an output variable of the RCA model for comparison to observed CBOD data. Internal coupling of the water quality model with Di Toro's (2001) sediment flux model is incorporated in RCA as well as other comparable water quality models such as WASP, EFDC and CE-QUAL-ICM (Testa et al., 2013). State variables of the sediment flux model include sediment bed organic carbon and nutrient content, porewater nutrient concentration, and benthic fluxes of inorganic nutrients, sulfide/methane, and dissolved oxygen (sediment oxygen demand).

Under the LIS-HWQMS project, the RCA code will represent light attenuation (Ke) and water clarity based on background light extinction, phytoplankton biomass (as Chl-a), Total Suspended Solids (TSS) and dissolved organic carbon (DOC) as a surrogate for Colored Dissolved Organic Matter (CDOM). HDR is currently performing correlation analyses between observed light extinction (Ke) and observed state variables (Chl-a, TSS, DOC) to determine spatially-dependent coefficients for the light attenuation relationship.

Unlike other comparable surface water models (e.g., ECOMSED, EFDC), the RCA water quality model does not include a sediment transport model that accounts for settling, deposition and resuspension processes for cohesive and non-cohesive sediments. Although TSS is a state variable in RCA, modeling of TSS was not incorporated in the previous SWEM application of RCA. As observed TSS in many watersheds is typically dominated by the non-volatile inorganic fraction of TSS, external loading is represented as the inorganic form of suspended sediment sources from watershed runoff, wastewater, stormwater and CSO discharges. Transport and fate of inorganic suspended sediment is represented by net settling of suspended sediment within the water column and from the water column to the sediment bed. Although resuspension is not explicitly modeled, this process is implicitly accounted for by parameterization of net settling velocity to the sediment bed. The organic fraction of suspended sediment is derived from RCA state variables for phytoplankton biomass and detritus. The output variable for TSS is then derived as the sum of the inorganic and organic forms of suspended solids for comparison to observed TSS measurements. This simplified approach based on net settling velocity was used in the CE-QUAL-ICM Chesapeake Bay estuary model (Cerco and Noel, 2004).

As an alternative to the net settling velocity approach described above, HDR has developed a simplified sediment transport model methodology that focuses on settling, deposition and resuspension processes for cohesive sediments. Bottom shear stress, simulated by a hydrodynamic model (e.g., ECOM), is linked to derive deposition and resuspension fluxes for the sediment transport model. This approach has been applied for Hudson River dredged material remediation assessments of toxic chemicals to support the Contamination Assessment and Reduction Project (CARP) project (HDR, 2019)).

Finally, a complete description of sediment transport processes for cohesive and non-cohesive solids could be incorporated in the LI Sound model framework in the future, if determined to be necessary to meet LIS-HWQMS project objectives and if required data are available. Rather than create new code, readily available source code for sediment transport processes should be used to model new state variables for cohesive and non-cohesive solids. ECOMSED-RCA sediment bed contamination applications for toxic chemicals incorporate sediment transport processes for cohesive and non-cohesive solids (ECOMSED) that are linked for input to the RCA water quality (HDR, 2014). HDR could use the sediment transport code available in ECOMSED to add new state variables for cohesive and non-cohesive solids to the RCA water quality model. The other option for HDR is to investigate coupling the ROMS sediment transport module (https://woodshole.er.usgs.gov/project-pages/sediment-transport/) within the ROMS-RCA framework that is currently being developed for the LIS-HWQMS.

From a conceptual model perspective, suspended sediments are but one of several components of light attenuation which, in turn, affects growth and production of phytoplankton, SAV and macroalgae. Final selection of the most appropriate approach for modeling TSS under the LIS-HWQMS project includes: (a) availability of data; and (b) the level of detail required to describe suspended sediment processes to (i) meet model performance targets for model calibration and validation; and (ii) address management objectives of the LIS-HWQMS related to hypoxia and the effect of external nutrient loading and eutrophication processes on living resources.

In summary, the ongoing LIS-HWQMS project includes the following major components:

- Linkage of watershed and atmospheric deposition loading with the hydrodynamic model (ROMS) and water quality model (RCA). Model setup, calibration, validation and evaluation of management scenarios are currently under development by HDR.
- Graphical User Interface (GUI) and Decision Support Tool (DST). Preliminary design efforts for the software tool are currently under development by HDR Team Member DHI.
- Linkage of living resource models with the hydrodynamic (ROMS) and water quality (RCA) models will be developed under a future contract.

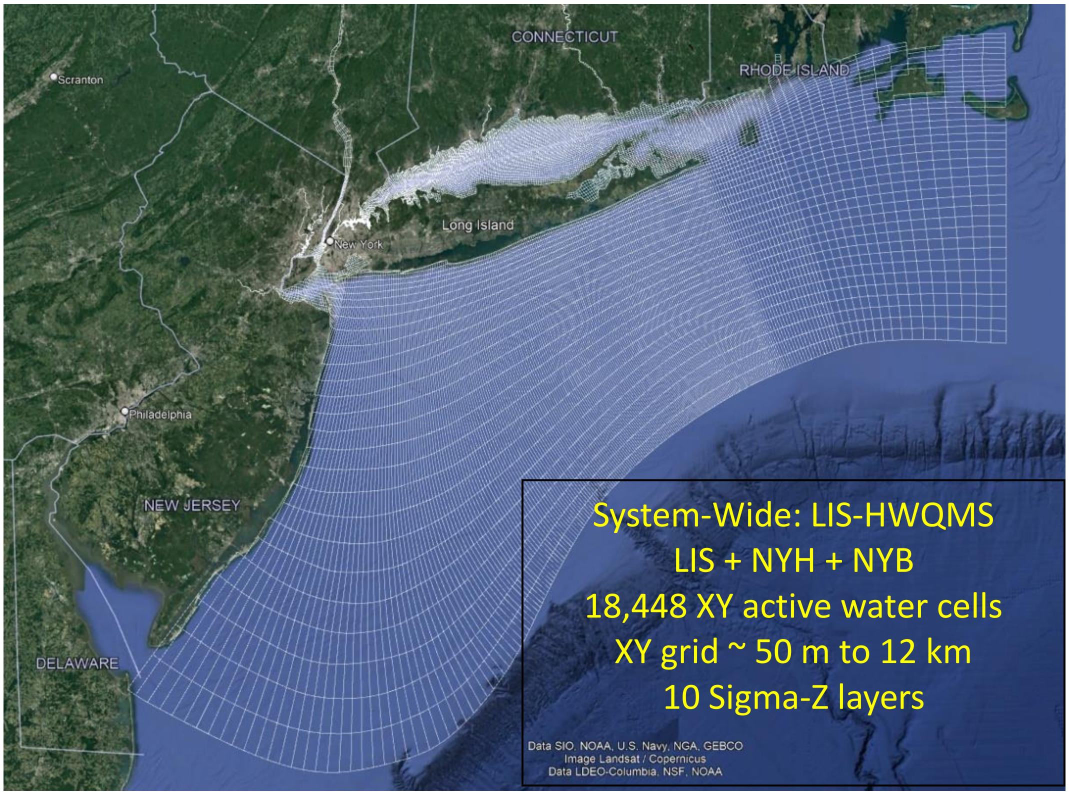

Figure 2-1 Integrated Modeling Framework Computational Grid for System-Wide Domain of Long Island Sound, New York Harbor and New York Bight. Currently there are 10 sigma-Z layers and the total system-wide domain includes 52,190 (307 x 170) land + active water grid cells.

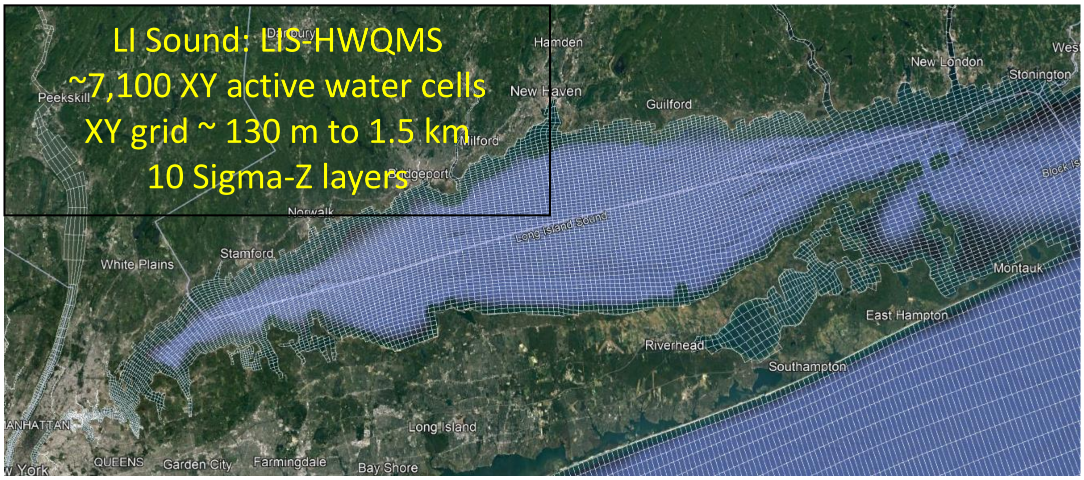

Figure 2-2 Integrated Modeling Framework Computational Grid for Long Island Sound.

2.2 Linkage of Living Resource Models with Hydrodynamic and Water Quality Models

As shown in Figure 2-3 the IMF will incorporate linkage of watershed loading with the LIS-HWQMS hydrodynamic/water quality models with living resource models. The integrated models will provide a science-based credible framework to support evaluations of the impact of nutrient management strategies on ecological and economic benefits associated with Living Resources.

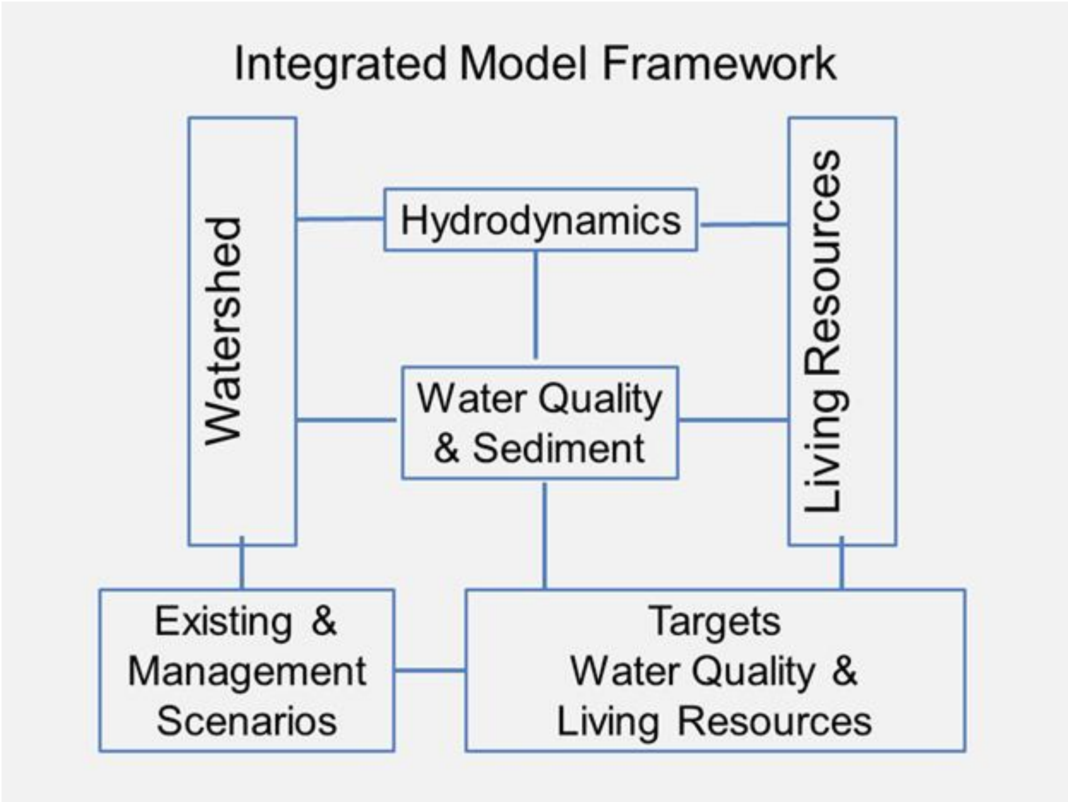

Figure 2-3 Integrated Model Framework for LI Sound Hydrodynamic-Water Quality-Living Resource Models

External watershed loading is driven by conditions based either on observed historical data or management scenarios. Watershed flow and loading then drives hydrodynamics and water quality conditions which, in turn, impact living resources. Water quality and ecological metrics, such as water clarity and abundance of SAV beds, are then used for comparison of waterbody conditions to targets or thresholds considered to be protective of designated uses for the waterbody. Consistent with EPA's "Nex-Gen" Strategy (USEPA, 2015), alternative nutrient management strategies are then evaluated with the integrated model framework to identify one or more strategies expected to achieve compliance with targets or thresholds. Required reductions of external nutrient loads can then be allocated to point and nonpoint sources through local planning within a coastal watershed (e.g., NPDES permits, BMPs, etc.) to attain compliance with water quality standards and waterbody-specific targets or thresholds to support designated uses.

Hydrodynamic and Water Quality Model Linkage: Coastal-estuarine hydrodynamics, water quality models can be simulated using either (a) standalone or internally coupled models that may be run (b) sequentially or simultaneously (Ganju et al., 2016). WASP, for example, is a well-known standalone water quality model that must be linked sequentially to hydrodynamic models (Wool et al. 2020). Examples of applications include Barnegat Bay (ROMS: Defne et al., 2017) and Norwalk Harbor (EFDC: Tetra Tech, 1995; RESPEC, 2022). As a 1-way standalone water quality model, the hydrodynamic model simulation is run, output is stored and post-processed to provide off-line input data to the WASP water quality model as a standalone model (ROMS: Defne et al., 2017 and EFDC: RESPEC, 2022). As an alternative approach to providing hydrodynamic results as input to a standalone water quality model, such as WASP, EFDC (https://dsi.llc/eems) and ROMS (https://www.myroms.org/) can also be configured to internally couple water quality/biogeochemical sub-model state variables with the hydrodynamic model. Examples of internal coupling of hydrodynamic and water quality models include the Peconic Estuary (EFDC: Tetra Tech, 1999) and Chesapeake Bay (ROMS-RCA: Testa et al., 2014).

Fig 2-4 shows schematic diagrams for linkage of hydrodynamic and water quality models as 1-way, off-line standalone and 2-way internally coupled options.

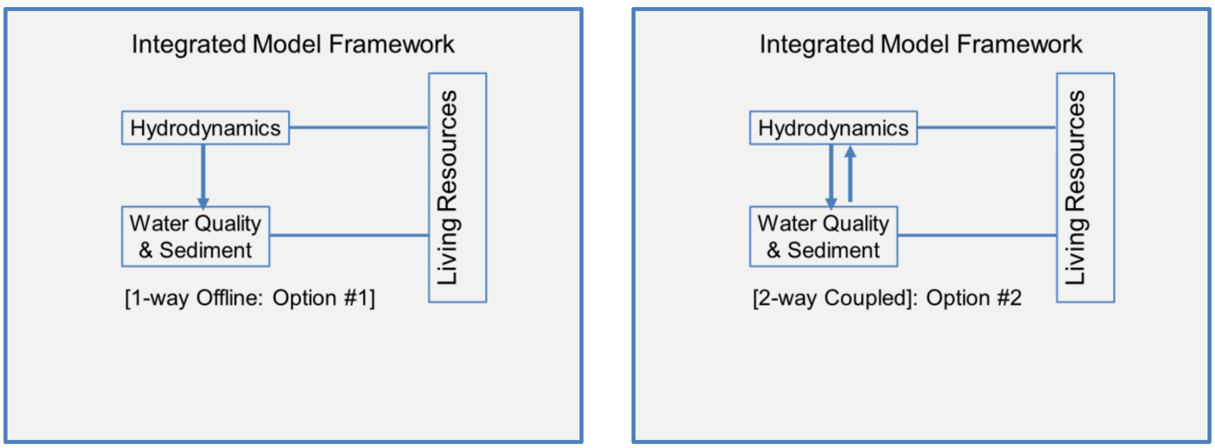

Figure 2-4 Options for Coupling Hydrodynamic and Water Quality Models

In the ECOMSED-RCA application for the SWEM, hydrodynamic model (ECOMSED) results were post-processed to provide 1-way off-line linkage between the hydrodynamic and RCA water quality model as a standalone model. This may be an option for HDR to consider for the LIS-HWQMS project to improve ROMS-RCA model runtimes (Figure 2-4 Option #1).

In addition to providing hydrodynamic results as input to standalone water quality models, such as WASP, ROMS (https://www.myroms.org/) can also be configured as 2-way linkage to internally couple the hydrodynamic and water quality models so that hydrodynamic and water quality state variables are both updated simultaneously at each time step. Following the approach used by Testa et al. (2014) for ROMS-RCA Chesapeake Bay models, HDR is currently internally coupling the ROMS hydrodynamic model with the RCA water quality model for the LIS-HWQMS project (Figure 2-4 Option #1).

Hydrodynamic, Water Quality and Living Resource Model Linkage: Figure 2-5 illustrates four options for linkage of hydrodynamic, water quality and living resource models. Note that the linkage shown for the models does not differentiate whether the models are (a) standalone and run off-line sequentially or (b) internally coupled and run simultaneously.

Figure 2-5 (A) shows 1-way linkage between the hydrodynamics, water quality and living resource models. In this first option, there is no feedback between any of the three models. In support of a TMDL evaluation for nitrogen loading to the Peconic Estuary, Tetra Tech (1999) developed an EFDC hydrodynamic and water quality model of the estuary and the surrounding open waters of Block Island Sound. As an example of 1-way linkage between water quality and living resources, the impact of a fixed distribution of macroalgae biomass on diurnal fluctuation of dissolved oxygen in the tidal creeks and shallow waters of the estuary was generated as a derived output variable. An analytical model of diurnal variability was internally linked within the EFDC water quality module to represent the impact of water depth and daily averages of dissolved oxygen, sediment oxygen demand, and production/ respiration of phytoplankton and macroalgae (Tetra Tech, 1989; Morton et al., 1990).

In the second option, Figure 2-5 (B) shows 2-way linkage between water quality and living resources. Chesapeake Bay living resources, for example, were represented with predictive models for oysters (Cerco and Noel, 2007, 2010) and SAV (Cerco and Moore, 2001). These living resource models provided dynamic feedback to the water quality model through filtration of particulate organic matter (oysters), uptake of nutrients (SAV) and changes in light attenuation and water clarity. In another example of 2-way linkage, an EFDC-WASP model of Norwalk Harbor was developed to support assessments of alternative strategies for reduction of wastewater nitrogen loading (Tetra Tech, 1995). The WASP model was modified to account for 2-way linkage between water quality and a fixed biomass distribution of dense beds of *Ulva lactuca*. The mass balance impact of *Ulva lactuca* on nitrogen sources and sinks was quantified with the 2-way model linkage to demonstrate its significance for nitrogen cycling in Norwalk Harbor.

As shown in Figure 2-5 [C], living resources can provide coupled feedback not only to water quality but also to hydrodynamics. In this case, the living resource model provides coupled feedback to the hydrodynamic model by increasing frictional drag that impacts shallow water circulation processes. Kalra et al. (2020), for example, used ROMS to develop an internally coupled model of SAV for West Falmouth Harbor in Cape Cod. The ROMS-SAV model represented coupled 2-way feedback between SAV, hydrodynamics (velocity and waves) and water quality (sedimentation dynamics, nutrient cycling, light attenuation and water clarity).

Finally, as shown in Figure 2-5 (D), the sediment transport component of a water quality model can provide 2-way coupled feedback to the hydrodynamic model via erosion, resuspension and deposition that can change bathymetry which, in turn, can change velocity and deposition conditions. An example of 2-way coupling between hydrodynamics and sediment transport and 2-way coupling of hydrodynamics and living resources is a COAWST / ROMS/ SWAN model developed for simulation of the impact of SAV on sediment dynamics under storm conditions in Chesapeake Bay (Biddle et al., 2022).

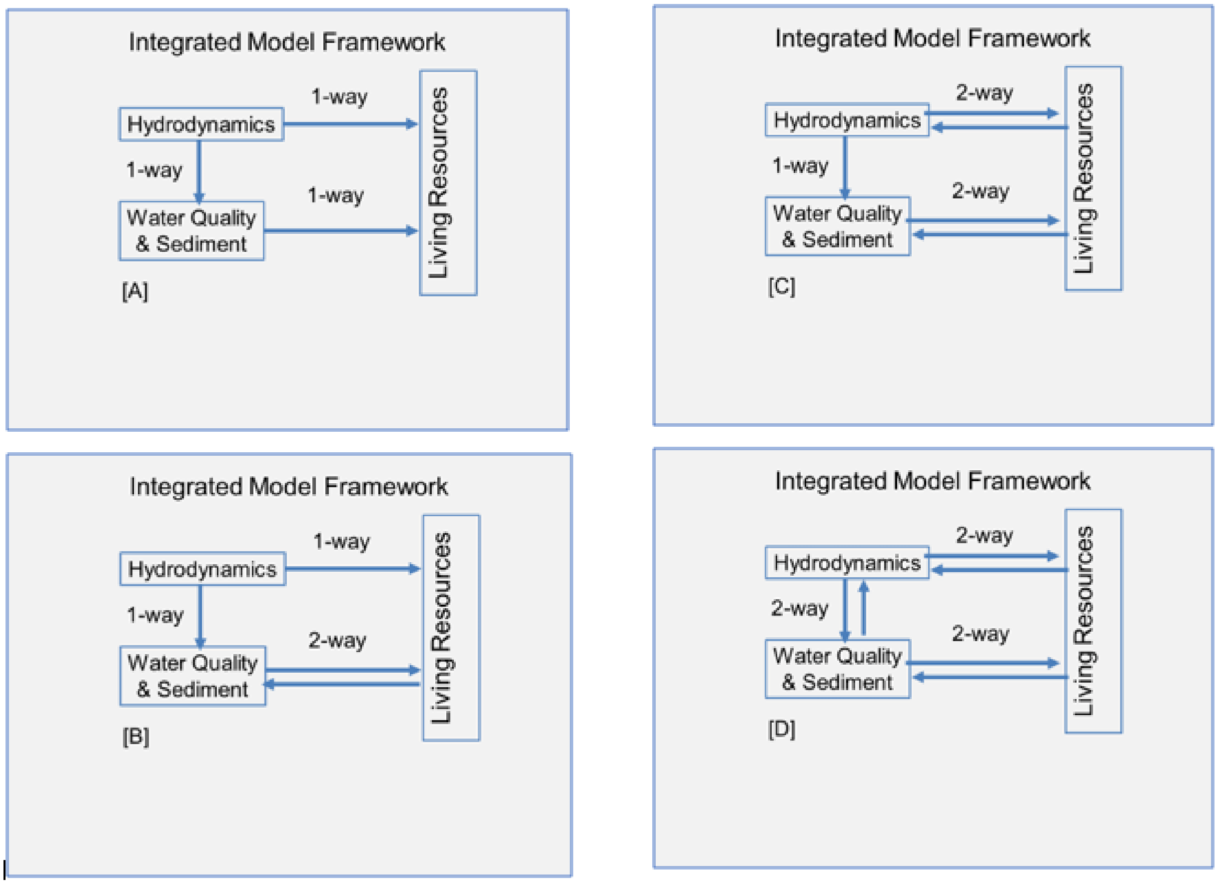

Figure 2-5 Options for Coupling Hydrodynamic and Water Quality Models with Living Resource Models

Table 2-1 presents a summary of key information related to the ROMS (hydrodynamic) and RCA (water quality) models under development for the LIS-HWQMS. Table 2-2 shows the simulation periods selected for ROMS-RCA hydrodynamic and water quality model calibration, validation and post-audit years.

Table 2-1 System-wide ROMS-RCA model under development by HDR for LIS-HWQMS. ROMS-RCA generated outputs will be available as driving input variables for linkage with Living Resource models.

Hydrodynamic & Water Quality Models	Model Time Step & Simulation Period	Model Spatial & Vertical Resolution	Model Outputs
ROMS Hydrodynamics	20 s time step Simulations from 2003 – 2022	52,190 horizontal cells (307 x 170) (land + active water) 18,448 water cells Currently 10 vertical sigma layers	Current velocity & Flow Water Temperature Water level Water depth Salinity Density as f (S, T)
RCA Water Quality & Sediment Flux	60 s time step Simulations from 2003 - 2022	52,190 horizontal cells (307 x 170) (land + active water) 18,448 water cells Currently 10 vertical sigma layers	Org & Inorganic (N, P, Si) Total-Inorganic-Sediment Org-C (Particulate & Dissolved) Dissolved Oxygen (DO) Phytoplankton (Chl-a) Bed organic (C, N, P, Si) Porewater (N, P, Si) Nutrient flux (N, P, Si) & Sediment Oxygen Demand (SOD)

Table 2-2 Simulation years for ROMS-RCA calibration (2005-2014); validation before (2003-2004) and after Nitrogen load reduction (2015-2018); and post-audit (2019-2022)

Year	Before N Reduction Validation (2003-2004)	Calibration (2005-2014)	After N Reduction Validation (2015-2018)	Post-Audit (2019-2022)
2000				
2001				
2002				
2003	X			
2004	X			
2005		●		
2006		●		
2007		●		
2008		●		
2009		●		
2010		●		
2011		●		
2012		●		
2013		●		
2014		●		
2015			☐	
2016			☐	
2017			☐	
2018			☐	
2019				✓
2020				✓
2021				✓
2022				✓

2.3 Section 2 References

Biddle, M.M., Palinkas, C.M. & Sanford, L.P. Modeling Impacts of Submersed Aquatic Vegetation on Sediment Dynamics Under Storm Conditions in Upper Chesapeake Bay (2022). *Estuaries and Coasts* 45, 130–147

Cerco, C., Moore, K., (2001). System-wide submerged aquatic vegetation model for Chesapeake Bay. Estuaries 24 (4), 522–534.

Cerco, C., and Noel, M., (2004). The 2002 Chesapeake Bay Eutrophication Model. Us Environmental Protection Agency, Region III Chesapeake Bay Program Office and US Army Corps of Engineers, ERDC, Environmental Laboratory, EPA 903-R-04-004, July 2004.

Cerco, C., and Noel, M., (2007). Can oyster restoration reverse cultural eutrophication in Chesapeake Bay? Estuaries and Coasts 30 (2), 331–343.

Cerco, C. and M. R. Noel (2010) Monitoring, modeling, and management impacts of bivalve filter feeders in the oligohaline and tidal fresh regions of the Chesapeake Bay system, Ecological Modelling 221 (2010) 1054–1064

Defne, Z., Spitz, F., DePaul, V., and Wool, T. (2017). “Toward a comprehensive water-quality modeling of Barnegat Bay; Development of ROMS to WASP coupler,” *Journal of Coastal Research*, DOI 10.2112/SI78-004.1.

Di Toro, D.M. (2001). *Sediment Flux Modeling*. Wiley-Interscience, New York, NY.

Fennel, K., Wilkin, J., Levin, J., Moisan, J., O’Reilly, J., and D. Haidvogel. (2006). Nitrogen cycling in the Middle Atlantic Bight: results from a three-dimensional model and implications for the North Atlantic nitrogen budget. Global Biogeochemical Cycles, 20:GB3007.

Ganju, N.K. et al. (2016) Progress and challenges in coupled hydrodynamic-ecological estuarine modeling. Estuaries and Coasts, 39(2):311-332.HDR (2014) Hydrodynamic and Sediment Transport Evaluation: Capping/Armoring Analyses for the Focused Feasibility Area, Appendix B1, 2014 Passaic River RI/FS Modeling Report (https://semspub.epa.gov/src/document/02/703641); EPA Records, Lower 8 Miles of Lower Passaic River, https://semspub.epa.gov/src/collection/02/AR63167

HDR (2019) Focused Feasibility Study Report, the Newtown Creek Superfund Site, Kings County and Queens County, New York City, New York Operable Unit 2, CERCLA Docket No. CERCLA-02-2018-2020, Prepared by NYC Dept. Environmental Protection as modified by US EPA, Region 2, November.

HDR (2021) Hydrodynamic & Water Quality Model Selection and Setup, New York City Department of Environmental Protection, DEP LIS-HWQMS Project, Contract: BEPA-LIS-HWQMS; PIN: 82619BEPALIS, June 11, 2021

HydroQual (2001a) Newtown Creek Water Pollution Control Project East River Water Quality Plan/ Task 10.0 System-Wide Eutrophication Model (SWEM)/Sub-Task 10.3 Calibrate SWEM Hydrodynamics. Report prepared for the City of New York, Department of Environmental Protection-New York under subcontract to Greeley and Hansen. 261 pp.

HydroQual (2001b) Newtown Creek Water Pollution Control Project East River Water Quality Plan / Task 10.0 System-Wide Eutrophication Model (SWEM) / Sub-Task 10.6 Validate SWEM Hydrodynamics.

Report prepared for the City of New York, Department of Environmental Protection-New York under subcontract to Greeley and Hansen. 312 pp.

HydroQual (2001c) Newtown Creek Water Pollution Control Project East River Water Quality Plan / Task 10.0 System-Wide Eutrophication Model (SWEM) / Subtask 10.4 Calibrate SWEM Water Quality / Subtask 10.6 Validate SWEM Water Quality. Report prepared for the City of New York, Department of Environmental Protection-New York under subcontract to Greeley and Hansen. 141 pp and appendices.

Kalra, T. S., Ganju, N. K., and Testa, J. M.: Development of a submerged aquatic vegetation growth model in the Coupled Ocean–Atmosphere–Wave–Sediment Transport (COAWST v3.4) model, Geosci. Model Dev., 13, 5211–5228, https://doi.org/10.5194/gmd-13-5211-2020, 2020.

RESPEC (2022) Norwalk Harbor Nutrient Modeling Plan, Topical Report RSI-3266, Prepared by RESPEC for Connecticut Dept. Energy and Environmental Protection, Hartford, CT, Project No. 4069.

Morton, M., A. Stoddard, and J. Pagenkopf (1990) Eutrophication and Nutrient Enrichment in the Peconic Estuary, Long Island: Numerical Model of Historical Conditions of the Mid-1970s, In: Spaulding, M. (ed), *Proceedings of ASCE Estuarine and Coastal Transport Modeling Conference*, Newport, RI, November 1989, pp. 351-360.

Testa, J.M., D.C. Brady, D.M. Di Toro, W.R. Boynton, J.C. Cornwell and W.M. Kemp (2013) Sediment flux modeling: Simulating nitrogen, phosphorus, and silica cycles. Estuarine, Coastal and Shelf Science 131 (2013):245-263

Testa, J.M., Y. Li, Y. Lee, M. Li, D. Brady, D. M. Di Toro, W. M. Kemp, and J. F. Fitzpatrick (2014). Quantifying the effects of nutrient loading on dissolved O2 cycling and hypoxia in Chesapeake Bay using a coupled hydrodynamic–biogeochemical model, Journal of Marine Systems, Vol. 139, Pages 139-158, ISSN 0924-7963, https://doi.org/10.1016/j.jmarsys.2014.05.018, (https://www.sciencedirect.com/science/article/pii/S092479631400147X)

Tetra Tech (1989). Water Quality Modeling for the Peconic Bay BTCAMP. Interim Progress Report No. 2, Prepared for Dvirka & Bartilucci, Syosset, NY and Suffolk County Dept. Health Services, Riverhead, NY. Prepared by Tetra Tech, Inc., Fairfax, VA, August 31.

Tetra Tech (1995). Hydrodynamic and Water Quality Mathematical Modeling Study of Norwalk Harbor, Connecticut. Draft Final Report prepared for City of Norwalk Dept. Public Works, Norwalk, CT by Tetra Tech, Inc., Fairfax, VA.

Tetra Tech (1999). Three-Dimensional Hydrodynamic and Water Quality Modeling of Peconic Estuary. Draft Final Report prepared for Peconic Estuary Program, Suffolk County Dept. Health Services, Riverhead, NY by Tetra Tech, Inc., Fairfax, VA.

USACE (2016) Hudson-Raritan Estuary Comprehensive Restoration Plan, Version 1.0, Volume 1, USACE New York District and Port Authority of NY & NJ, June. http://www.nan.usace.army.mil/Portals/37/docs/harbor/Final%20CRP_2016-06-27_v1.0.pdf?ver=2016-06-29-170128-157

USEPA (2015) Evolving the Long Island Sound Nitrogen Reduction Strategy, US Environmental Protection Agency, December 2015. US Environmental Protection Agency, Region 1 (Boston, MA) and Region 2

(New York City, NY). December. https://longislandsoundstudy.net/wp-content/uploads/2016/02/LIS-Nitrogen-Strategy-Enclosures-12-23-15-1.pdf

Wool, T.; Ambrose, R.B., Jr.; Martin, J.L.; Comer, A. 2020. WASP 8: The Next Generation in the 50-year Evolution of USEPA's Water Quality Model. *Water,12*,1398. https://doi.org/10.3390/w12051398

3. DEP Scope of Work for Integrating Living Resource Models

As described in Section 1, EPA initiated the Long Island Sound Study (LISS) in 1985 as a State-Federal partnership to control point source (PS) and nonpoint source (NPS) pollutant loading to mitigate the occurrence of hypoxic conditions in Western Long Island Sound. Planning efforts focused on control of PS and NPS nutrient loading because of the cause-effect linkage between external loading, nutrient enrichment, eutrophication, seasonal stratification and seasonal hypoxia in LI Sound. In addition to eutrophication and hypoxia, coastal nutrient enrichment also results in poor water clarity which leads to degradation of habitat conditions to sustain healthy meadows of submerged aquatic vegetation (SAV). As the primary nutrient limiting phytoplankton production in marine waters, State-Federal water quality management efforts focused on reduction of nitrogen loading for development of a LI Sound TMDL as a strategy to control the occurrence of hypoxia. Following approval of the TMDL by EPA in 2001, investments in upgrading wastewater treatment facilities achieved reductions in nitrogen loading that exceeded the target established by the TMDL (see Figure 1-3).

Despite the significant progress made to reduce nitrogen loading, EPA's "Nex-Gen" Strategy (USEPA, 2015) expanded the hypoxia-driven focus of nutrient management efforts to also include assessments of the impacts of nutrient enrichment on living resources in the open waters and coastal waters of LI Sound. EPA's strategy included the recommendation to

> "*Address eutrophication-related impacts by translating narrative nutrient criteria into numeric N thresholds that are protective of designated uses*".

USEPA (2015) recommended that Numeric Nutrient Thresholds for nitrogen be established for (1) coastal watershed-embayments and nearshore waters; (2) tributary watersheds; and (3) Western LI Sound coastal watersheds characterized by direct discharge of large wastewater treatment facilities. EPA noted that Numeric Nutrient Thresholds can be specified for either ambient nitrogen concentrations or external nitrogen loading rates to achieve targets deemed protective of SAV to support restoration or maintenance of habitat.

3.1 Living Resources Components of Integrated Model Framework

DEP (2019) *Developing Living Resource Management Models for LIS Integrated Model Framework (IMF* Ecological resources of interest for development of Living Resource model components of the LI Sound Integrated Model Framework include:

- Submerged Aquatic Vegetation (SAV) model to derive water clarity-based SAV threshold targets for restoration with representation of positive feedbacks that control water clarity
- Shellfish models (oysters, clams, mussels) to account for effects of shellfish filtration on water quality and water clarity
- Assess use of macroalgae (seaweed) or other Living Resource for bioextraction options for quantification of nitrogen management strategies

As described in Section 2, the components of the Integrated Modeling Framework (IMF) consist of system-wide hydrodynamic (ROMS) and water quality (RCA) models that will be linked with Living Resources models. The IMF will provide a defensible numerical model framework to support water quality management and Living Resource project objectives including:

- Derive site-specific Numeric Nutrient Criteria (NNC) to achieve water clarity threshold targets for restoration of SAV in coastal embayments;
- Assess macroalgae (seaweed) and shellfish for bioextraction, aquaculture and "green" technologies as Best Management Practices (BMPs) for *in-situ* nutrient management strategies;
- Assess climate change impacts on Living Resources with linkage to the system-wide ROMS-RCA hydrodynamic – water quality model framework.

Under the LIS-HWQMS project, the Integrated Modeling Framework will be designed and implemented to evaluate the benefits and effectiveness of alternative nutrient management strategies to meet targets (e.g., increase eelgrass extent by 2,000 acres) identified in the LI Sound Comprehensive Conservation Management Plan (CCMP). EPA and DEP's key guiding objective for the LIS-HWQMS project and linkage with Living Resource models is to ensure that State-Federal nutrient management strategies are based on defensible science.

3.2 DEP Scope of Work for Living Resources Models

Scope of Work tasks for the Living Resources project are listed in Table 3-1.

Table 3-1 List of Tasks

Tasks to be completed for linkage of living resources models into Integrated Model Framework (Source: DEP (2019)	
Task No.	Description
Task 1	Project Scoping includes Technical Advisory Committee for Living Resources to Inform and assist DEP to develop RFP requirements to achieve living resources objectives for project
Task 2	Develop regional system-wide scale forecast model to link living resources with system-wide LIS-HWQMS under future condition scenarios (e.g., climate change)
Task 3	Pilot testing at local embayment-tidal river scale to link living resources with existing embayment-tidal river hydrodynamic and water quality models; open boundary conditions to be extracted from system-wide LIS-HWQMS
Task 4	Pilot testing of management questions for evaluation of bioextraction and "green" nitrogen removal strategies with living resource models using LIS-HWQMS generated nutrient conditions under existing and future scenarios.

3.3 Technical Advisory Committee (TAC) for Living Resources Models

Under Task 1 of the Scope of Work, a Technical Advisory Committee (TAC) for Living Resources has been assembled by DEP. The TAC is charged with providing DEP with technical advice, peer review services and recommendations for integration of Living Resource models with the ROMS-RCA hydrodynamic and water quality model being developed by HDR under the LIS-HWQMS project. Recommendations of the TAC will be used to inform and assist DEP in identifying and refining an RFP for Living Resources models.

During the period from July through December 2022, TAC members and support team personnel planned and participated in a Kick-off Meeting and three (3) TAC Workshop meetings; provided input to a literature review for an inventory of Living Resource models; and contributed to preparation of draft and final TAC reports. As part of their review to inform TAC recommendations to DEP, TAC members were asked to address a series of questions related to the following three (3) items:

- Part 1: Report Section 5 - Review of Living Resource Models
- Part 2: General Questions about Living Resource Models
- Part 3: Tasks to be completed for linkage of Living Resource Models into Integrated Model Framework

Project Development Team and TAC Members for Living Resources are listed in Table 3-2.

Table 3-2 Project Development Team and TAC Members for Living Resources

Team and TAC Members (*) and Affiliation
David Lipsky, Project Director, NYCDEP
Gregory Wilkerson, Project Manager, NYCDEP
Mark Tedesco, Director, EPA Long Island Sound Office, Long Island Sound Study
Melissa Duvall, EPA Region 2 Modeling and Data Coordinator, Long Island Sound Study
Andrew Stoddard (*) Chair, Dynamic Solutions, LLC
Lewis Linker (*) CBP Modeling Coordinator, EPA Chesapeake Bay Program Office
Suzanne Bricker (*) Physical Scientist, NOAA NOS NCCOS, Oxford Laboratory
Julie Rose (*) Research Ecologist, NOAA Fisheries, NEFSC Milford Laboratory
Kristin Kraseski (*) Bioextraction Coordinator, NYS DEC and NEIWPCC
Shaye Sable, Project support, Dynamic Solutions, LLC

The following materials related to the TAC, this technical report, and the online TAC meetings are presented at the end of this report:

- Section 9 - Short biographies of TAC members are presented in Section 9 of this report.
- Section 10 - Separate document with attachments
- Attachment 1 – DEP Draft Scope of Work for Living Resources (2019)
- Attachment 2 – Kick-off Meeting Agenda and Presentation (Aug-24-2022)
- Attachment 3– TAC Workshop #1 Agenda and Presentation (Sept-20-2022)
- Attachment 4 – TAC Workshop #2 Agenda and Presentation (Oct-13-2022)
- Attachment 5 – TAC Workshop #3 Agenda and Presentation (Nov-10-2022)
- Attachment 6 – TAC Team Responses to Questions about Living Resource Models

3.4 Section 3 References

DEP (2019) *Developing Living Resource Management Models for LIS Integrated Model Framework (IMF),* 2019 Long Island Sound Study CCMP Enhancement Proposal Submitted to US EPA Long Island Sound Office, Stamford, CT by New York City Dept. Environmental Protection (DEP), Bureau of Environmental Planning and Analysis, Flushing, NY.

USEPA (2015) Evolving the Long Island Sound Nitrogen Reduction Strategy, US Environmental Protection Agency, December 2015. US Environmental Protection Agency, Region 1 (Boston, MA) and Region 2 (New York City, NY). December. https://longislandsoundstudy.net/wp-content/uploads/2016/02/LIS-Nitrogen-Strategy-Enclosures-12-23-15-1.pdf

4. Applications of Living Resources for Nutrient Management

4.1 Introduction and Background

Nitrogen has been identified as a primary nutrient limiting phytoplankton growth in estuaries such as Long Island Sound (Howarth and Marino 2006; Ryther and Dunstan 1971). Reductions of nitrogen inputs from coastal watersheds have been targeted by resource management programs seeking to reduce the effects of eutrophication in the coastal and estuarine environment. In the United States, permitting through the National Pollution Discharge Elimination System (NPDES), created by the Clean Water Act (33 U.S.C. §§1251-1387), has been used to regulate nitrogen sources. NPDES permits for nitrogen require point source nitrogen dischargers to limit both the volume of effluent discharged, as well as the concentration of nitrogen within the effluent, as these two characteristics determine the overall load of nitrogen to receiving waters. One tool for nitrogen reduction in waterbodies with persistent impairments has been to identify the total maximum daily load (TMDL), an approach that predicts the total amount of nitrogen that a waterbody can receive while still maintaining good water quality (Copeland 2001). The TMDL is then used to set nitrogen reduction goals that form the basis for state and local nitrogen management plans (USEPA 2002). The Long Island Sound Nitrogen TMDL has been in place for more than two decades (NYSDEC and CTDEP 2000).

Reductions of point sources of nitrogen through NPDES permit limitations have been major contributors to nitrogen management in Long Island Sound over the last several decades. Nitrogen input from point sources may be reduced by limiting both the volume of effluent discharged and the concentration of nitrogen it contains (USEPA 2010). The major point sources of nitrogen in the Long Island Sound watershed are municipal wastewater treatment plants (WWTPs). Technological advances in wastewater treatment targeting enhanced nitrogen removal have enabled effluent from plants to reach N concentrations as low as 3 mg N L^{-1} (Grady et al. 2011). In the portions of the Long Island Sound watershed with high population densities that produce millions of gallons of effluent daily, such as those found in New York City and the western Sound, this may still represent a substantial amount of organic and inorganic nitrogen entering the coastal environment. Research indicates that effluent inorganic nitrogen is bioavailable and even some of the effluent organic nitrogen is biologically available (Bronk et al. 2010).

As point source reduction programs have been successfully implemented within the states of Connecticut and New York, there has been a growing recognition of the important contributions of nonpoint sources of nitrogen to continued water quality impairments in some parts of the Sound. While point sources of nitrogen have a well-defined effluent stream, nonpoint sources of nitrogen are diffuse in nature and more challenging to regulate and remediate. One nonpoint source of nitrogen that has been regulated by NPDES permits are municipal separate storm sewer systems (MS4s); structures within an urbanized area that collect stormwater and discharge it to local waterways (Minan 2005). Other common nonpoint sources of nitrogen not covered by NPDES permits include runoff from fertilized suburban lawns and golf courses, atmospheric deposition of nitrogen from car, industrial, and agricultural emissions, and septic systems. Methods for nonpoint source nutrient reduction may involve the construction of physical impediments to reduce the volume of runoff and increase nitrogen removal (e.g. vegetative buffers, permeable reactive barriers, swales), development of advanced septic system technologies targeting nitrogen removal, sewering areas that are dependent on septic systems, emissions regulation, and fertilizer sale restrictions. Implementation of nonpoint source reduction practices in densely populated areas may be expensive and require regular maintenance to ensure continued effectiveness (Houle et al. 2013; Stephenson et al. 2010).

Ongoing nitrogen management within Long Island Sound and its watershed is challenged by technological limits to point source controls, costs, and the diffuse nature of non-point sources. These challenges are magnified by continued population increases in the coastal watershed. The development of additional tools to reduce nitrogen impacts to the Sound is needed. In-situ, or assimilative, nitrogen reduction practices increase the total amount of nitrogen that can enter a waterbody while still achieving water quality standards. Examples of assimilative nitrogen reduction practices that have been included in existing nitrogen management plans in the United States include floating wetland construction (White and Cousins 2013), stream and wetland restoration (Craig et al. 2008), and algal turf scrubber technology (Mulbry et al. 2010). These assimilative practices reduce nitrogen by sequestration in enhanced biomass. The sequestered nitrogen is either retained in a stable habitat (floating wetlands; stream and wetland restoration) or harvested (algal turf scrubber technology).

Two groups of organisms increasingly being considered for use in assimilative nitrogen reduction approaches are bivalve shellfish and seaweeds (Rose et al. 2014; Kim et al. 2015). Seaweeds incorporate dissolved nitrogen into their tissues as they grow; bivalve shellfish remove nitrogen from the water column by feeding on plankton or detrital material and incorporating some of the nitrogen from their food into tissue and shell as they grow (Officer et al 1982). Shellfish and seaweed may offer an inexpensive mechanism to concentrate and sequester nitrogen. By enhancing natural populations through restoration or aquaculture practices, the assimilative capacity of an impaired waterbody for nitrogen can be increased.

4.2 Living Resources Models and Integrated Model Framework for LI Sound

The Integrated Model Framework will incorporate linkage of watershed loading with the LIS-HWQMS hydrodynamic and water quality models with living resource models (see Figure 2-3). The integrated models will thus provide a science-based credible framework to support evaluations of the impact of nutrient management strategies on ecological and economic benefits associated with Living Resources.

External watershed loading is driven by conditions based either on observed historical data or management scenarios. Watershed flow and loading then drives hydrodynamics and water quality conditions which, in turn, impact living resources. Water quality and ecological metrics, such as water clarity and abundance of SAV beds, are then used for comparison of waterbody conditions to targets or thresholds considered to be protective of designated uses for the waterbody. Consistent with EPA's "Nex-Gen" Strategy (USEPA, 2015), alternative nutrient management strategies are then evaluated with the integrated model framework to identify one or more strategies expected to achieve compliance with targets or thresholds.

Required reductions of external nutrient loads can then be allocated to point and nonpoint sources through local planning within a coastal watershed (e.g., NPDES permits, BMPs, etc.) to attain compliance with water quality standards and waterbody-specific targets or thresholds to support designated uses. Management strategies that improve water clarity in an embayment, for example, may support restoration efforts to re-establish a healthy community of SAV such as eelgrass beds, which can lead to restoration of desirable fishery resources. As described in this section, living resources can be considered as viable nutrient management strategies using "green" technologies in combination with traditional "gray" technologies (e.g., wastewater and stormwater reductions; BMPs) to demonstrate compliance with waterbody-specific targets or thresholds to support designated uses.

4.3 Living Resources as Strategies for Nutrient Management

The cultivation and harvest of shellfish and seaweed can be considered a nutrient management strategy because, as these species grow within coastal waters, they incorporate nutrients into their tissue (and for shellfish, also their shells), which are then removed from the water upon harvest. Land-based nutrient reduction strategies seek to manage nitrogen from point and nonpoint sources by reducing the source. 'Nutrient bioextraction' as defined above, is a management tool that can be used in the water to address the excess nutrients from all sources, including legacy nitrogen that is already present. Within the Long Island Sound, there has been interest in nutrient bioextraction since at least 2009, when LISS and others hosted an 'International Workshop on Bioextractive Technologies for Nutrient Remediation' to promote new and innovative technologies for the management of eutrophication and hypoxia in the Sound.

Please note that other species do take up nitrogen into their tissue as they grow, for example, submerged aquatic vegetation, however, this section of the report focuses only on species that can be cultivated and harvested from the water. Submerged aquatic vegetation serve important ecological functions as spawning or breeding areas, nurseries, and food sources, and in some areas, has been identified as "essential fish habitat" and protected under the Magnuson-Stevens Act. In the context of nutrients, seagrass meadows have been identified as important sites of nitrogen transformation in estuaries (Zarnoch et al. 2107). Therefore, increased submerged aquatic vegetation is an important ecosystem target within the Long Island Sound, but not a potential candidate for bioextraction activities.

4.3.1 Bivalve Shellfish

In addition to filtration of particles and assimilation of nitrogen into shellfish tissue and shell, shellfish can contribute to nitrogen reduction through other mechanisms, including enhancement of denitrification in adjacent sediments, and increased burial of biodeposits in sediments. Because shellfish are filter-feeding animals that consume seston such as phytoplankton and detritus, they remove particulate matter from the water column and have the additional benefit of increasing water clarity. Species of interest for bioextraction in Long Island Sound include the Eastern Oyster (*Crassostrea virginica*), the Atlantic Ribbed Mussel (*Geukensia demissa*), the hard clam/quahog (*Mercenaria mercenaria*), and the blue mussel (*Mytilus edulis*). These species may naturally prefer different habitat, may feed on different components of the seston, and their potential use for bioextraction may vary according to local conditions.

Shellfish are part of approved nutrient management plans outside of the Long Island Sound, including at the municipal scale in Massachusetts and the regional scale in Chesapeake Bay. The Mashpee Comprehensive Watershed Nitrogen Management Plan, for the Town of Mashpee in Massachusetts (Town of Mashpee Sewer Commission, 2015), lists shellfish propagation as a key aspect of their recommended plan, and as an early implementation item that they believe will fast-track the water quality improvements needed in the targeted eutrophic waterbodies. The plan tries to maximize the use of shellfish aquaculture, specifically oysters and quahogs, to reduce the need to expand expensive traditional sewering infrastructure. The Town also has the dual goal of restoring their historic shellfish resources. This strategy will be assessed periodically as the plan is implemented, through the use of monitoring and modeling to determine the extent of nitrogen removal following implementation of shellfish aquaculture, and adapted if water quality goals are not being achieved.

In the Chesapeake Bay, an expert panel put forth recommendations in 2016 about the use of oyster aquaculture as a best management practice for nitrogen and phosphorus removal. They concluded that available data were sufficient to support the use of nitrogen and phosphorus assimilation and harvest of oyster tissue for private oyster aquaculture practices in the following categories: Off-bottom Private Oyster Aquaculture Using Hatchery-Produced Oysters, On-bottom Private Oyster Aquaculture using Hatchery-Produced Oysters, and On-bottom Private Oyster Aquaculture Using Substrate Addition (Cornwell et al. 2016). This best management practice has been approved for use by jurisdictions in watershed implementation plans to meet nutrient reductions required by the Chesapeake Bay TMDL for nitrogen and phosphorus. Expert panel consideration of nutrient reduction services provided by restored oyster reefs is ongoing.

Oysters

The Eastern Oyster (*Crassostrea virginica*) is a high value native species that, as mentioned above in association with both nutrient management programs, is known for its nitrogen removal potential. Oysters are cultivated sub-tidally in Long Island Sound using varied methods, and annual harvests can vary depending on local site conditions such as food quality and quantity, disease and predation, salinity, dissolved oxygen, etc. Bricker et al. (2018) reported that Connecticut oyster bioextraction (removal from the water through harvest) at current cultivation levels could potentially remove 1% of the total watershed nitrogen input to the Long Island Sound with a service value of $8.5-230.3 million annually. This does not include oyster harvest in New York, nor denitrification losses from Connecticut or New York oyster operations, which can be equal to or greater than removal by sequestration into tissue and shell. Estimated nitrogen removal by combined harvest and denitrification losses in Connecticut and New York show that removal could potentially be as great as one third the annual nitrogen load to the Sound, with cultivation of 5% of the bottom area.

Ribbed Mussels

Ribbed mussels (*Geukensia demissa*) have been proposed as bioextractive species for impaired waterbodies, as their poor taste and absence of commercial market minimize poaching risk to human health (Galimany et al. 2017). They are a native species commonly found in salt marshes, and can filter a broad range of particle sizes relative to other shellfish (Moody and Kreeger, 2021). Net nitrogen removal capacity by ribbed mussels was calculated to be 0.18 g for a typical animal grown suspended from a commercial mussel raft in a pilot study in the Bronx River Estuary, NY (Galimany et al. 2017).

Blue Mussels

Blue mussels (*Mytilus edulis*) have an existing industry with well-developed cultivation methods, though they have lower commercial value than oysters (Rose et al. 2015). Like ribbed mussels, they are native to many areas within the Long Island Sound. They have not previously been used in nutrient bioextraction programs in the US, and perhaps are less likely to be used in such programs because unlike ribbed mussels, they are a commonly eaten species by humans. The use of blue mussels for nutrient bioextraction has been explored in Denmark, where a full production scale study was performed in Skive Fjord, and demonstrated a nitrogen removal rate of 0.6-0.9 t N ha^{-1} $year^{-1}$ (Petersen et al. 2014). Their results suggested that the costs of nutrient removal by mussels were lower than some land-based nitrogen reduction measures.

Hard Clams

Hard clams (*Mercenaria mercenaria*), also known as quahogs, are native to the Long Island Sound and are a high-value product in the commercial food market. Unlike the other species mentioned in this document, hard clams are an infaunal group that must be planted in sediments, and therefore their production is limited by available seafloor space (Rose et al. 2015). Quahogs have been assessed for their nitrogen extraction potential in the nearshore waters of Cape Cod, and were shown to be an average 0.67% nitrogen by total dry weight, with a mean 0.22 g N/animal (Reitsma et al. 2017).

4.3.2 Seaweed

As seaweeds grow, they remove inorganic nutrients from the surrounding water, and like shellfish, once harvested, remove those nutrients from the system entirely. Growing seasons of seaweed vary based on species, and cultivation techniques have been developed for some species native to the Northeastern US, including kelp and red seaweed (*Alaria esculenta*, *Laminaria digitata*, *Saccharina latissima*, *Gracilaria tikvahiae*, *Chondrus crispus*, *Palmaria palmata*, and *Pyropia/Porphyra*) (Rose et al. 2015). Seaweed can be consumed as a human food, and used as animal feeds, cosmetics, or biofuel, and there is also recent local interest in its use as a fertilizer amendment or soil amendment (see the following website for recordings of the May 2022 Long Island Sound Seaweed Bioextraction Symposium for more information about local projects: Nutrient Bioextraction: Extracting Pollution from the Sound - Long Island Sound Study).

Seaweeds are being investigated for bioextraction in other states, including Maine (Grebe et al. 2021) and Alaska (Kim et al. 2019), many countries across the globe, including Korea (Park et al. 2021) and European countries, such as Denmark, where growing Saccharina latissima to recapture nutrients is considered to be in line with the EU Marine Strategy Framework (Bruhn et al. 2016). Recent work out of the University of California, Santa Barbara, using the Gulf of Mexico as a case study, suggest that seaweed aquaculture may be a cost-effective and feasible tool for nutrient assimilation in nutrient polluted areas (Racine et al. 2021) Seaweed, however, is not part of any approved nutrient management plans within the US.

Sugar Kelp

Sugar kelp (*Saccharina latissima*) is a cold water, brown algal species that is native to the Long Island Sound and the northeastern US. Kim et al. (2015) found that sugar kelp could remove between 38 and 180 kg N ha^{-1} within the Long Island Sound in a growing season, with kelp grown in the mouth of the Bronx River Estuary performing better than other sites in western and central Long Island Sound, likely due to higher nitrogen levels in the water throughout the season. Temperature, salinity, light, currents, cultivation density, and the timing of farm deployment and harvesting will all impact growth and nutrient removal by sugar kelp (Grebe et al. 2021). Sugar kelp is grown on simple horizontal lines placed in the water, at a depth that is appropriate for optimal light availability; the grow-out systems themselves require little maintenance (Redmond et al. 2014).

Gracilaria

Gracilaria tikvahiae is a red seaweed species native to New England that grows in the summer months. *Gracilaria* species are commercially cultivated throughout the world for human food and other products (Pereira and Yarish). It has the benefit of being fast-growing, tolerant of a range of environmental conditions, easy to propagate and can store high concentrations of nitrogen in its tissue (Hanisak, 1987). *Gracilaria tikvahiae* was first grown in the Long Island Sound for bioextractive purposes in 2011 and 2012 in an investigation by Kim et al. (2014) to determine nitrogen removal rates for the species. The researchers found that *Gracilaria* removed an estimate of 28 to 94 kg N ha^{-1} at Fairfield, CT, and Bronx River Estuary sites, respectively; and an estimated \$311 and \$940 ha^{-1} in the potential economic value of nitrogen sequestration, respectively. *Gracilaria* can be grown in tank systems (as is permitted in Connecticut), or through suspended rope culture. In a tank system, seaweed fronds float freely, unattached to any structures, and inputs can be highly controlled to reduce contamination. More relevant to nutrient bioextraction, *Gracilaria* can also be grown, attached to lines in open water, similar to grow-out systems for sugar kelp, but unlike sugar kelp, where the algae's holdfast structure connects it to the line, *Gracilaria* must be attached to the line by either tying it, or entwining it through the line (Redmond et al. 2014).

Other Species

Ulva lactuca, or sea lettuce, is a species of green algae that has worldwide distribution, including the northeastern US. *Ulva* has been identified as a potential species for nutrient bioextraction due to its fast growth, ease of cultivation, and rapid uptake of organic materials (Gao et al. 2017). There may be hesitation in the local cultivation of this species for bioextraction due to some of the same characteristics that make it easy to cultivate, which is that it is so fast growing that it is sometimes involved in blooms that harm marine environments and have potential human health impacts as well due to vapors released upon decomposition (Dominguez and Loret, 2019).

Chondrus crispus, or Irish moss, is a red seaweed (Phylum Rhodophyta) that is an important commercial species used for its carrageenan, which have applications in the food and pharmaceutical industries. It is often collected through wild harvest at low tide in New England, but can also be grown in tank-based systems, though that has high operation and labor costs (Redmond et al. 2104). *Chondrus* has been suggested for use as a bioextractive species (Grizzle, 2011), and has been grown in open water trials in Prince Edward Island, Canada (Chopin et al. 1999), and Baja California (Zertuche-Gonzalez et al. 2001), but have not been used specifically for nutrient bioextraction in the Long Island Sound.

Porphyra and *Pyropia*, also known collectively as nori, are red seaweeds that are commonly cultivated in Asia. Three species, *Porphyra purpurea*, *Porphyra umbilicalis*, and *Pyropia leucosticta*, are found along the north Atlantic coast between Canada and the Long Island Sound (Redmond et al. 2014). *Porphyra* and *Pyropia* have not been used for nutrient bioextraction within the Long Island Sound or surrounding regions.

4.4 Future Outlook for Bioextraction as "Green" Nutrient Management Technology

Implementation of large-scale bioextraction projects within the Long Island Sound is currently limited by economic and regulatory considerations, but it is continuing to be studied because of its appeal as a cost-effective in-water nitrogen removal strategy, and the acknowledgement of states and municipalities that land-based nitrogen reduction strategies will not be sufficient in many embayments to reduce nitrogen levels to desired targets.

4.4.1 Shellfish (bivalves)

Recent studies have shown that eastern oysters, hard clams, and blue mussels can provide net removal of nutrients through filtration from the water of seston (phytoplankton, detritus) as they feed (Clements and Comeau 2019; Reitsma et al. 2017). There are already local (e.g., Mashpee, MA) and regional (e.g., Chesapeake Bay) examples of mechanisms to include shellfish aquaculture as a nutrient management strategy within TMDLs and 208 plans. The well-established oyster and clam aquaculture industry in the Sound has existed for over 100 years, and examples of application elsewhere provides a starting point for development of the shellfish industry as a nutrient bioextraction component that could be added to a comprehensive nutrient management plan. The cultivation of oysters and clams for human consumption is limited to certified waters; New York has been exploring the potential for large-scale implementation of a noncommercial species, *Geukensia demissa* or the ribbed mussel, for pathogen and nutrient reductions in waters that are closed due to high bacterial abundance.

4.4.2 Seaweed

Commercial cultivation of seaweeds in the Long Island Sound is currently limited by economic and regulatory factors. In Connecticut, there are only two species of seaweed that are approved for commercial cultivation, *Saccharina latissima* and *Gracilaria tikvahaie*. *Saccharina* is only allowed to be grown in shellfish-certified waters, and *Gracilaria* only in tank-based systems, to ensure that they are safe for human consumption. According to Connecticut Sea Grant, there are 8 commercial operations permitted in Connecticut. Seaweed production in the region has to compete with cheaper imports, which limit its expansion somewhat. In New York, there are currently no permitted commercial growers, though there is interest and numerous pilot projects ongoing.

For the greatest benefit regarding nutrient bioextraction, there will be a need to cultivate and harvest seaweed species in impaired, or uncertified waters, and there is not a clear path forward for that within the Long Island Sound at this point in time. It is hoped that continued investigation into nutrient bioextraction projects with seaweed and into markets for such products will make this possible in the near future.

4.5 Section 4 References

Bradley, M. and S. Paton. 2018. Tier 1 2017 Mapping of *Zostera marina* in Long Island Sound and Change Analysis. The University of Rhode Island, U.S. Fish and Wildlife Service, and USGS. https://longislandsoundstudy.net/wp-content/uploads/2019/03/LIS_2017_report_eelgrass_FINAL.pdf

Bricker, S.B., J.G. Ferreira, C. Zhu, J.M. Rose, E. Galimany, G. Wikfors, C. Saurel, R. Landeck Miller, J. Wans, P. Trowbridge, R. Grizzle, K. Wellman, R. Rheault, J. Steinberg, A. Jacob, E.D. Davenport, S. Ayvazian, M. Chintala, and M.A. Tedesco. (2018). Role of shellfish aquaculture in the reduction of eutrophication in an urban estuary. Environmental Science & Technology, 52:1, 173-183.

Bronk, D.A., Roberts, Q.N., Sanderson, M.P., Canuel, E.A., Hatcher, P.G., Mesfioui, R., Filippino, K.C., Mulholland, M.R., and Love, N.G. (2010). Effluent organic nitrogen (EON): bioavailability and photochemical and salinity-mediated release. Environmental Science & Technology 44, 5830-5835.

Bruhn, A., D.B. Torring, M. Thomsen, P. Canal-Verges, M.M. Nielsen, M.B. Rasmussen, K.L. Eybye, M.M. Larsen, T.J.S. Balsby, J.K. Petersen. 2016. Impact of environmental conditions on biomass yield, quality, and bio-mitigation capacity of *Saccharina latissima*. Aquaculture Environment Interactions, 8, 619-636.

Chopin, T., G. Sharp, E. Belyea, R. Semple, and D. Jones. 1999. Open-water aquaculture of the red alga *Chondrus crispus* in Prince Edward Island, Canada. Sixteenth International Seaweed Symposium.

Clements, J.C., and Comeau, L.A. (2019). Nitrogen removal potential of shellfish aquaculture harvests in eastern Canada: A comparison of culture methods. Aquaculture Reports 13, 100183.

Copeland, C. (2001). "Clean Water Act and Total Maximum Daily Loads (TMDLs) of Pollutants". (CRS Report for Congress, order code 97-831 ENR: Available online at https://www.everycrsreport.com/files/20011030_97-831ENR_b93c671be775f89dd6c46f204fda171b84aa61d0.pdf).

Cornwell, J., J. Rose, L. Kellogg, M. Luckenbach, S. Bricker, K. Paynter, C. Moore, M. Parker, L. Sanford, B. Wolinski, A. Lacatell, L. Fegley, K. Hudson. 2016. Panel Recommendations on the oyster BMP nutrient and suspended sediment reduction effectiveness framework and nitrogen and phosphorus assimilation in oyster tissue reduction effectiveness for oyster aquaculture practices. Oyster BMP expert panel first incremental report 1, 197. https://www.oysterrecovery.org/wp-content/uploads/2017/01/Oyster-BMP-1st-Report_Final_Approved_2016-12-19.pdf

Craig, L.S., Palmer, M.A., Richardson, D.C., Filoso, S., Bernhardt, E.S., Bledsoe, B.P., Doyle, M.W., Groffman, P.M., Hassett, B.A., Kaushal, S.S., Mayer, P.M., Smith, S.M., and Wilcock, P.R. (2008). Stream restoration strategies for reducing river nitrogen loads. Frontiers in Ecology and the Environment 6, 529-538.

Dominguez, H. and E.P. Loret. 2019. *Ulva lactuca*, a source of troubles and potential riches. Marine Drugs 17, 357.

Gao, G., S.A. Clare, C. Rose, and G.S. Caldwell. 2017. *Ulva rigida* in the future ocean: potential for carbon capture, bioremediation, and biomethane production. Glob. Change Biol. Bioenergy, 10(1), pp. 39-51.

Grady, C.P.L., Jr, Daigger, G.T., Love, N.G., and Filipe, C.D.M. (2011). Biological wastewater treatment. IWA Publishing.

Grizzle, Raymond E., "Development of guidelines for using bioextraction technologies to manage nutrients in New Hampshire's estuarine waters" (2011). PREP Reports & Publications. 11.

Grebe, G. S., Byron, C. J., Brady, D. C., Geisser, A. H., & Brennan, K. D. (2021). The nitrogen bioextraction potential of nearshore *Saccharina latissima* cultivation and harvest in the Western Gulf of Maine. *Journal of Applied Phycology*, *33*(3), 1741-1757. https://link.springer.com/article/10.1007/s10811-021-02367-6

Hanisak, M.D. 1987. Cultivation of Gracilaria and other macroalgae in Florida for energy production. In Bird, K.T., Benson, P.H. (Eds.), Seaweed Cultivation for Renewable resources. Elsevier, New York, pp. 191-218.

Houle, J., Roseen, R., Ballestero, T., Puls, T., and Sherrard, J. (2013). A comparison of maintenance cost, labor demands, and system performance for LID and conventional stormwater management. Journal of Environmental Engineering 139, 932-938.

Howarth, R.W., and Marino, R. (2006). Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: evolving views over three decades. Limnology and Oceanography 51, 364-376.

Hudson, R., T.E. Kutcher, J.M. Rose, M.S. Dixon. 2016. Ribbed mussel nutrient bio-extraction pilot project. Kingston, RI.

Kim JK, Kraemer GP, Yarish C (2014) Field scale evaluation of seaweed aquaculture as a nutrient bioextraction strategy in Long Island Sound and the Bronx River Estuary. Aquaculture 433: 148-156.

Kim JK, Kraemer GP, Yarish C (2015) Use of sugar kelp aquaculture in Long Island Sound and Bronx River Estuary for nutrient extraction. Mar. Ecol. Prog. Ser. 531:155–166.

Kim, J., M. Stekoll, C. Yarish. 2019. Opportunities, challenges and future directions of open-water seaweed aquaculture in the United States. Phycologia, 58:5, 446-461, DOI:10.1080/00318884.2019.1625611

Minan, J.H. (2005). Municipal Separate Storm Sewer System (MS4) regulation under the Federal Clean Water Act: the role of water quality standards? San Diego Law Review 42, 1215-1257.

Moody, J., and D. Kreeger. 2021. Spatial distribution of ribbed mussel (*Geukensia demissa*) filtration rates across the salt marsh landscape. Estuaries and Coasts, 44:1, 229-241.

Mulbry, W., Kangas, P., and Kondrad, S. (2010). Toward scrubbing the bay: Nutrient removal using small algal turf scrubbers on Chesapeake Bay tributaries. Ecological Engineering 36, 536-541.

NYSDEC and CTDEP (2000) A Total Maximum Daily Load Analysis to Achieve Water Quality Standards for Dissolved Oxygen in Long Island Sound, Prepared by New York State Dept. of Environmental Conservation, Albany, NY and Connecticut Dept. of Environmental Protection, Hartford, CT, December.

Officer, C.B., Smayda, T.J., and Mann, R. (1982). Benthic filter feeding: a natural eutrophication control. Marine Ecology Progress Series 9, 203-210.

Park, J. S., Shin, S. K., Wu, H., Yarish, C., Yoo, H. I., & Kim, J. K. (2021). Evaluation of nutrient bioextraction by seaweed and shellfish aquaculture in Korea. Journal of the World Aquaculture Society, 52(5), 1118-1134

Petersen JK, Hasler B, Timmermann K et. al. (2014) Mussels as a tool for mitigation in the marine environment. Mar. Pollut. Bull. 82:137–143

Racine, P., Marley, A., Froehlich, H. E., Gaines, S. D., Ladner, I., MacAdam-Somer, I., & Bradley, D. (2021). A case for seaweed aquaculture inclusion in US nutrient pollution management. Marine Policy, 129, 104506.

Redmond, Sarah; Green, Lindsay; Yarish, Charles; Kim, Jang; and Neefus, Christopher, "New England Seaweed Culture Handbook" (2014). Seaweed Cultivation. 1.

Reitsma, J., D.C. Murphy, A.F. Archer, R.H. York. 2017. Nitrogen extraction potential of wild and cultured bivalves harvested from nearshore waters of Cape Cod, USA. Marine Pollution Bulletin 116:1, 175-181.

Rose, J.M., S.B. Bricker, S. Deonarine, J.G. Ferreira, T. Getchis, J. Grant, J.K. Kim, J.S. Krumholz, G.P. Kraemer, K. Stephenson, and G.H. Wikfors. 2015. Nutrient bioextraction. Encyclopedia of sustainability science and technology, 10, 2015.

Rose, J.M., Bricker, S.B., Tedesco, M.A., and Wikfors, G.H. (2014). A Role for Shellfish Aquaculture in Coastal Nitrogen Management. Environmental Science & Technology 48, 2519-2525.

Ryther, J.H., and Dunstan, W.M. (1971). Nitrogen, phosphorus and eutrophication in the coastal marine environment. Science 171, 1008-1013.

Stephenson, K., Aultman, S., Metcalfe, T., and Miller, A. (2010). An evaluation of nutrient nonpoint offset trading in Virginia: a role for agricultural nonpoint sources? Water Resources Research 46, W04519.

Town of Mashpee Sewer Commission. 2015. Final recommended plan/final environmental impact report. Comprehensive Wastewater Management Plan, Town of Mashpee. Hyannis: GHD Inc

USEPA (2002). "Guidelines for reviewing TMDLs under existing regulations issued in 1992". (Office of Water, Washington D.C.: Available online at https://www.epa.gov/sites/production/files/2015-10/documents/2002_06_04_tmdl_guidance_final52002.pdf).

USEPA (2010). "National Pollution Discharge Elimination System (NPDES) Permit Writer's Manual". Office of Water: Office of Wastewater Management, Water Permits Division, Washington D.C. Available online at https://www.epa.gov/npdes/npdes-permit-writers-manual.

USEPA (2015) Evolving the Long Island Sound Nitrogen Reduction Strategy, US Environmental Protection Agency, December 2015. US Environmental Protection Agency, Region 1 (Boston, MA) and Region 2 (New York City, NY). December. https://longislandsoundstudy.net/wp-content/uploads/2016/02/LIS-Nitrogen-Strategy-Enclosures-12-23-15-1.pdf

White, S.A., and Cousins, M.M. (2013). Floating treatment wetland aided remediation of nitrogen and phosphorus from simulated stormwater runoff. Ecological Engineering 61, 207-215.

Zarnoch, C.B., T.J. Hoellein, B.T. Furman, and B.J. Peterson, 2017. Eelgrass meadows, *Zostera marina (L.)*, facilitate the ecosystem service of nitrogen removal during simulated nutrient pulses in Shinnecock Bay, New York, USA. Marine Pollution Bulletin, 124: 1, 376-387).

Zertuche--González, J.A., García-Lepe, G., Pacheco-Ruiz, I., Gendrop, V., and J.M. Guzmán. 2001. Open water *Chondrus crispus* Stackhouse cultivation. J. Appl. Phycol. 13: 249-253.

5. Review of Living Resource Models: A Primer

This section provides: a brief summary of the key living resources of interest in LIS; the ecosystem services provided by those living resources; and, provides conceptual diagrams on the role played by these resources in nutrient cycling and interactions with coastal marine ecosystems. Much of the summary information for the living resources was available through the Long Island Sound Study Habitat Restoration Initiative (LISS 2003; LISS 2018). The LISS has supported multiple habitat restoration and living resource studies related to nutrient bio-extraction and estimation of ecosystem services (EPA Long Island Sound Study http://longislandsoundstudy.net/).

5.1 Living Resources for LI Sound Integrated Model Framework

Living resources being considered for the Long Island Sound Integrated Model Framework include:

- Submerged Aquatic Vegetation (SAV)
- Shellfish (oysters, clams, mussels)
- Seaweed (macroalgae)

An overview description of each of these species groups of living resources follows.

5.1.1 Shellfish

Shellfish are an important living resource in the LIS – providing valuable commercial and recreational fisheries; filtration of phytoplankton and particulate organic matter (POM) important to eutrophication, water quality and clarity; bio-extraction and sequestration of carbon; and structural habitat via reefs used by other invertebrates and small fish for refuge (Coen et al. 2007, Grabowski and Peterson 2007). Figure 5-1 is a conceptual diagram from NOAA showing the ecosystem benefits of oysters. The figure demonstrates how healthy oyster reefs improve water quality by filtering phytoplankton from the water column, while also providing hard substrate for other biota and reducing sediment resuspension. The primary factors influencing oysters and other shellfish distribution and reef maintenance include salinity, temperature, food availability, water depth or low DO, total suspended solids (TSS), pH, and available hard substrate or existing reef to support spawning and larval settlement (Figure 5-1, some factors shown as ecosystem stressor in second panel).

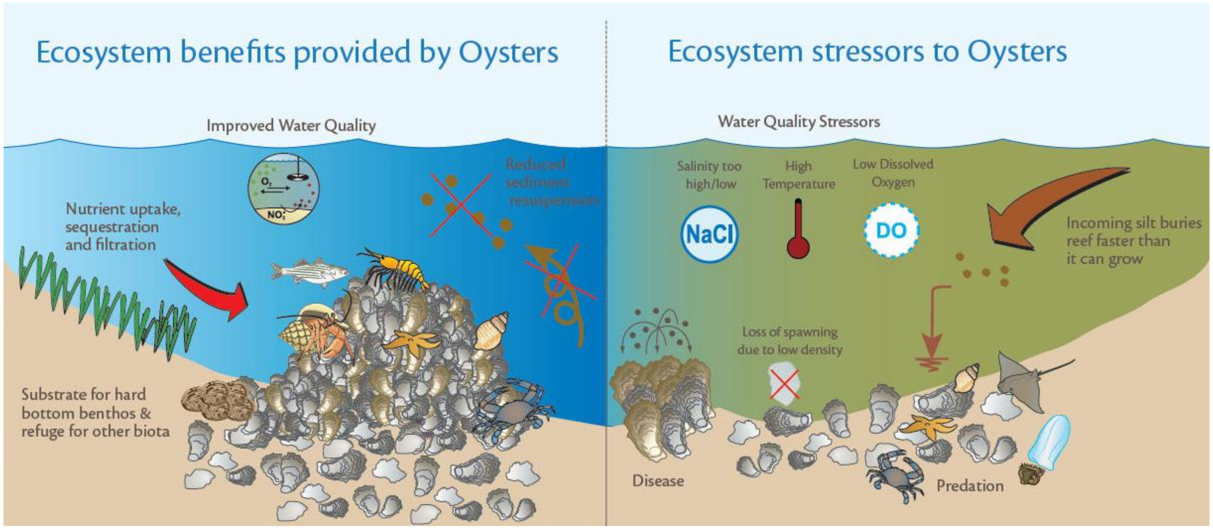

Figure 5-1 Ecosystem benefits of oysters and ecosystem stressors to oysters. Image courtesy of Chesapeake Bay NOAA Office (http://chesapeakebay.noaa.gov/oysters/oyster-reefs).

There are multiple species of shellfish that are commercially and recreationally harvested for human consumption in LIS. Annual oyster, clam, and scallop harvests are indicative of both abundances as well as the socioeconomic importance to Long Island Sound. Oysters are reef forming shellfish, where clams burrow in intertidal mud flats, and bay scallops use eelgrass beds. In 2019, the Connecticut Department of Agriculture recorded oyster harvest over $16 million dollars, and hard clam harvest over $6.6 million dollars in the state's shellfish grounds (https://portal.ct.gov/DOAG/Aquaculture1/Aquaculture/Shellfish-Industry-Profile). Bay scallops have been low in LIS waters with continued die-offs recorded in recent years (https://www.nytimes.com/2019/11/07/nyregion/peconic-bay-scallop-season.html). Harvest of shellfish is only allowed in approved waters, and so it is an indication of water quality in the embayments (LISS 2018). Areas with poor water quality in LIS are closed to shellfishing. Shellfish beds are regularly monitored by state regulatory agencies to assure that shellfish harvested in commercial and recreationally approved areas are safe for consumption. In Connecticut, fishers can only harvest on their own leased beds. Connecticut shellfish beds cover about 80,000 acres (Figure 5-2, Aquaculture Mapping Atlas, https://shellfish.uconn.edu/maps/). In New York, including outside of LIS, commercial shellfisheries were valued at greater than $10 million dollars in 2016 (New York State Department of Environmental Conservation).

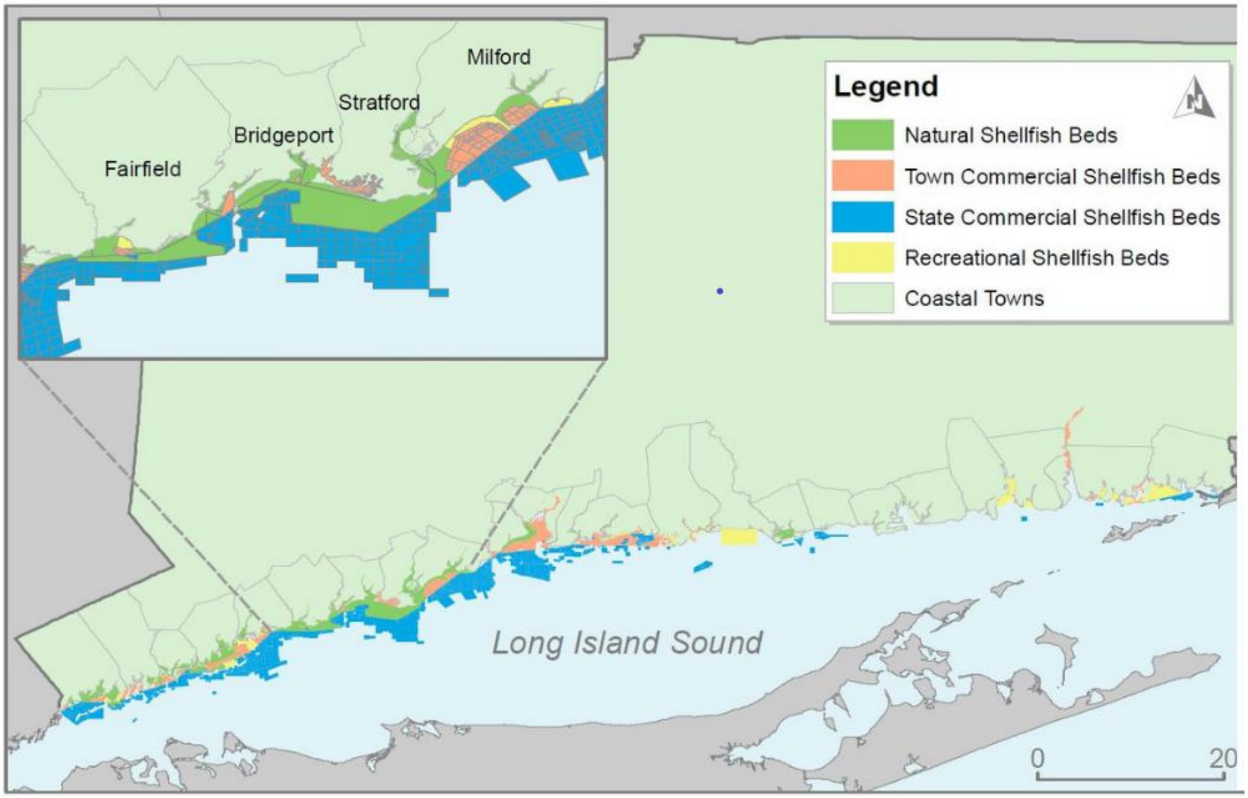

Figure 5-2 Map by M. Zuber at the Aquaculture Mapping Atlas https://shellfish.uconn.edu/maps/)

Shellfish can filter extremely large volumes of water. Oysters have particularly high filtration rates that are dependent on oyster size, water temperature, salinity, particulate organic matter (POM, e.g., phytoplankton) sizes and concentration, TSS, and flow across the reefs (Shumway 1996, Riisgård 2001; TSS citation as needed). Shellfish remove inorganic particulate matter (e.g. suspended solids) and organic particulate matter (e.g. phytoplankton) from the water column and thereby playing a role in cycling N, P, and Si in the water column and improving water clarity and quality. The three-dimensional structure of oyster reefs can also reduce the flow and direction of water, thereby processing nutrients at a high rate (Dame et al. 1984). This is an especially important ecosystem service as excessive nitrogen and other pollutants from land-based human activities have degraded coastal water quality, impacting marine habitats and animals in Long Island Sound (LISS 2018).

Farmed shellfish can also provide similar ecosystem services. Nutrients, such as nitrogen and phosphorus, are often found in excess in our coastal waters due to the overuse of fertilizers on lawns and farms. Nutrient 'bioextraction' is the practice of farming and harvesting shellfish (or seaweed) for the purpose of removing nitrogen and other nutrients from natural water bodies (EPA Long Island Sound Study http://longislandsoundstudy.net/). This nutrient removal service is quantified using numerical ecosystem models (e.g., Ferreira et al. 2011, Rose et al. 2015a, 2015b, Bricker et al. 2020), and the overall value of shellfish harvest has recently been assessed in the Long Island Sound (Bricker et al. 2015, 2018).

The LISS describes natural shellfish beds in Section 7 of the 2018 Habitat Restoration Initiative, Technical Support for Coastal Habitat Restoration (LISS 2018). These natural shellfish beds provide habitat and predation refuge for small invertebrates and fish. The primary reef forming shellfish species are the eastern oyster (*Crassostrea virginica*), the ribbed mussel (*Guekensia demissa*), the blue mussel (*Mytilus edulis*) and the northern horse mussel (*Modiolus modiolus*). The oyster is the most common of the habitat-forming species. Most natural oyster beds are close to shore and near to the mouths of the tidal rivers (LISS 2018). The most common mussel species, the blue mussel, forms extensive subtidal beds, though some intertidal beds exist. At the time of the LISS 2018 Report, the abundance and distribution of blue mussels in the LIS had not been well-documented. The northern horse mussel inhabits deeper waters of the Sound and is much less common than the aforementioned species. The ribbed mussel is commonly found along the fringes of salt marshes where it occupies a niche habitat embedded in the peat, attached to other mussels, and *Spartina* spp. plants. It can occur at densities exceeding 1000 individuals per square meter (Dreyer and Niering 1995). There are more recent studies to evaluate the ecosystem services of blue and ribbed mussels in LIS within coastal embayments that support larger abundances of these species (e.g., Brinton 2021).

5.1.2 Submerged Aquatic Vegetation (SAV)

SAV beds are comprised of rooted plants, such as eelgrass and widgeon grass, that grow in shallow embayments below the spring low-tide water level mark. SAV is a critical marine resource and is currently protected by both Federal (Clean Water Act; 33 U.S.C. 26 section 1251 et seq) and state legislation (Connecticut Coastal Management Act Chapter 444, Sections 22a-90 to 22a-112, New York Seagrass Protection Act). In addition, monitoring the extent of SAV is a critical component of the Long Island Sound Study's (LISS) 2020 Comprehensive Conservation and Management Plan (longislandsoundstudy.net). Bradley and Paton (2018) further state that many commercially important finfish and shellfish species are directly dependent on SAV beds for refuge, spawning, attachment, and food (Laney 1997). The Atlantic States Marine Fisheries Commission (www.asmfc.org) has a stated policy on the assessment, protection, and study of SAV as an Essential Fish Habitat (EFH) as a recommendation for all member States (ASMFC Habitat Committee, 1997). SAV beds also provide the ecosystem services of improving water quality and clarity, and stabilizing shallow intertidal habitat in the embayments. SAV beds trap sediments in the water column and along the bottom, and use DIN and DIP from the water column (Buzelli et al. 1998, Vaudrey et al. 2020), thereby improving water quality and clarity (LISS 2003).

Eelgrass, *Zostera marina*, is the perennial habitat forming seagrass in Connecticut and New York State coastal polyhaline (18-30 ppt salinities) waters that provides ecosystem services, improves the seabed, and supports coastal resilience (LISS 2003, NYSDEC 2017). Estimates from historic records suggest ~200,000 acres of eelgrass were in NY waters during the 1930's, while as of 2009 only 21,803 acres currently remain (NYS STF 2009). The decline in New York seagrass has been attributed to a multiple stressor response to changes in water quality, nutrient enrichment, water temperature, and physical disturbances (NYSDEC 2017).

Factors influencing SAV distribution and growth include water column depth, light availability, nutrient concentrations, temperature, current velocity, wave energy, and salinity (Kemp et al. 2004, Vaudrey et al. 2013, 2019). In Long Island Sound, eelgrass is found at depths between 1.8 and 12 feet below mean low water (Koch and Beer, 1996; Koch et al. 2001). Light availability is measured in two ways – the percent light through the water (PLW) column and percent light at the leaf (PLL) for determining habitat suitability or optimum light conditions to support eelgrass (see Figure 5-3, Kemp et al. 2004, Vaudrey et al. 2013). Nutrient concentrations (DIN, DIP) are additionally necessary for SAV photosynthesis, but also can inhibit SAV growth if planktonic and epiphytic algae are using the nutrients to cause algal blooms and shading (Figure 5-3). Eelgrass bed growth is highest during summer months in LIS (NYSDEC 2017).

Koch et al. 2001 measured seagrasses in minimum current velocities between 3-18 cm s^{-1} and maximum flows between 50 and 180 cm s^{-1}.

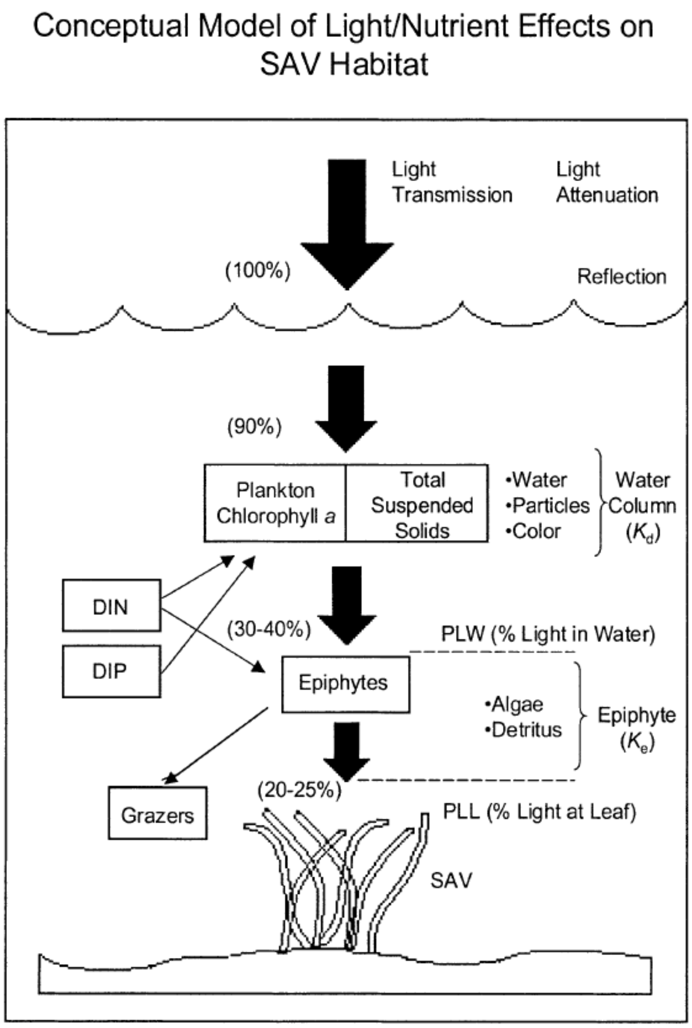

Figure 5-3 Conceptual model from Kemp et al. 2004 demonstrating how light availability to support photosynthesis by SAV is influenced by dissolved and particulate matter in the water column and by epiphytic algae on the plant leaves. DIN and DIP stimulate growth of the planktonic and epiphytic algae, which can be controlled by grazing (Kemp figure modified from Batiuk et al. 1992, Dennison et al. 1993).

Bradley and Paton (2018) completed a Tier 1 2017 Long Island Sound survey were similar to previous Tier 1 surveys conducted by USFWS including to: 1) conduct a comprehensive survey of SAV (primarily eelgrass) using similar methods as the previous surveys, and 2) examine broad trends of eelgrass in the Long Island Sound Study area. The areal extent of the eelgrass survey from 2017 is shown inFigure 5-4. The areal extent measured in the field for the four regions in Connecticut is shown in Figure 5-5.

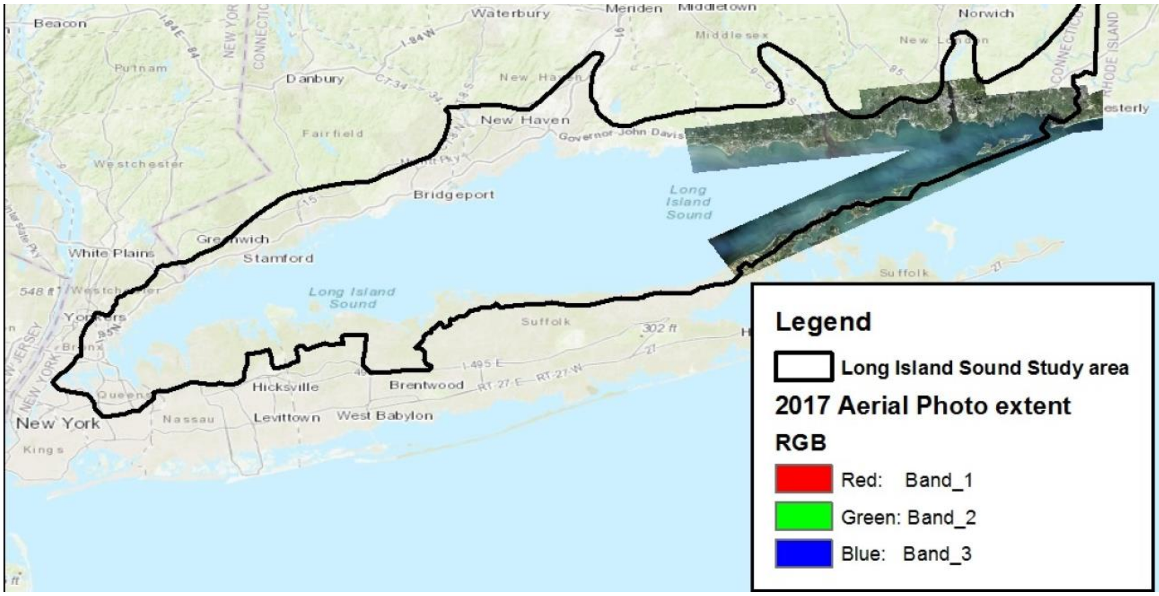

Figure 5-4 Areal extent of eelgrass survey in 2017 by Bradly and Paton (2018)

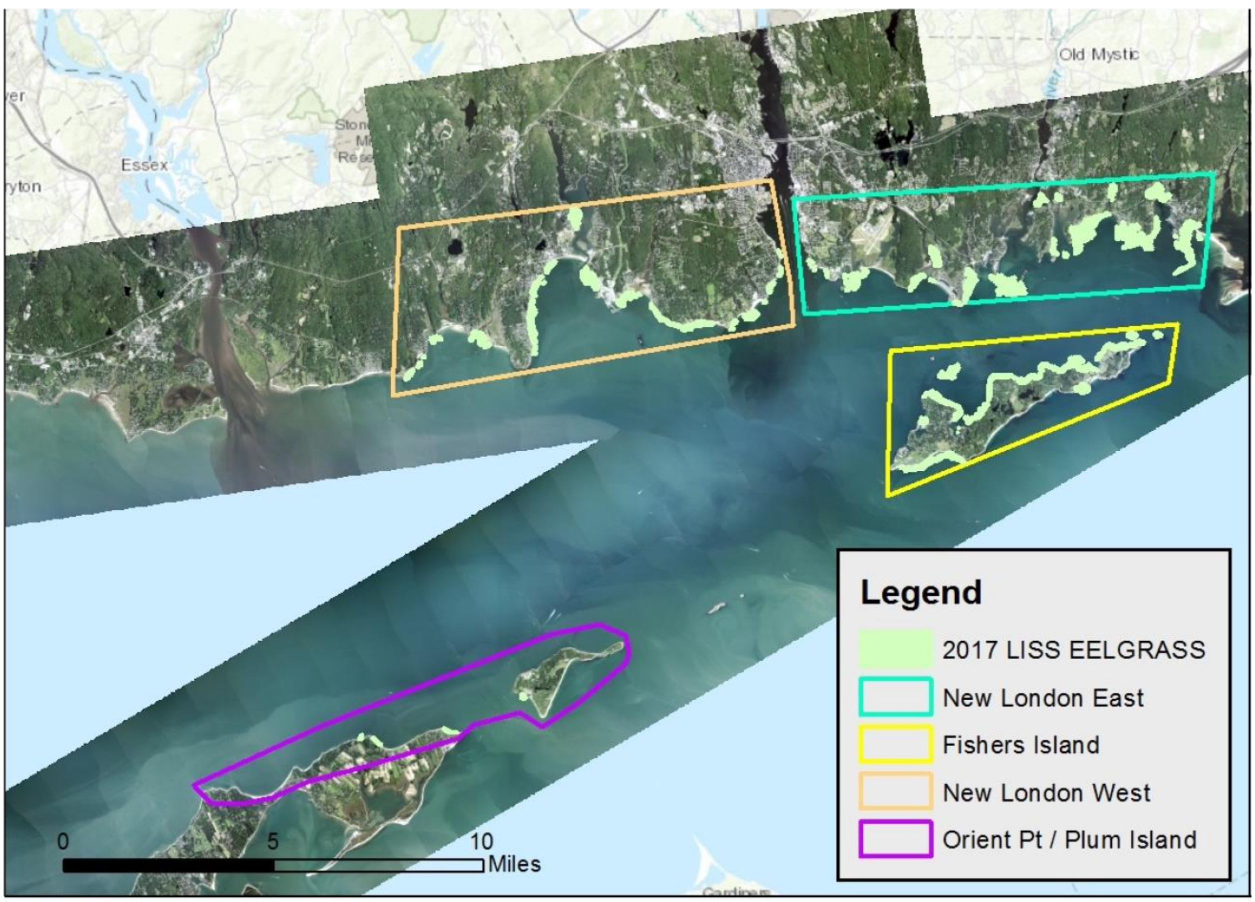

Figure 5-5 Areal extent of eelgrass mapped by areas in 2017 by Bradley and Paton (2018).

5.1.3 Seaweeds

Seaweeds are large marine algae that can be harvested from the wild or cultivated (https://seaweedhub.org/). There are many seaweeds that have been identified in Long Island Sound to occur naturally from the surf zone to open waters, and during warmer summer months to year-round (Stewart van Patten and Yarish 2009). Sugar kelp (*Saccharina latissima*) and *Gracilaria tikvahaie* are cultivated in Long Island Sound waters and by tanks for human consumption (https://seaweedhub.org/). Sugar kelp is a large brown seaweed that thrives in colder waters of Long Island Sound, and has been the focus of ocean aquaculture due to its ecological and economic benefits. Kelp is a winter crop. where farmers seed juvenile kelp on long lines attached to buoys or docks in November and December, and then harvest the fast-growing crop in the spring. *Gracilaria* is a warm water species growing from June to October in Long Island Sound. The Long Island Sound Study has supported multiple studies by Dr. Charles Yarish at the University of Connecticut on farm-cultured kelp in LIS. Dr. Yarish has harvested kelp as long as 8 meters (26.2 feet) from culture sites, and notes that wild kelp also grows naturally to as long as seven meters (23 feet) in Long Island Sound.

As primary producers, seaweeds assimilate dissolved inorganic nitrogen and phosphorus, and carbon dioxide (Roleda and Hurd 2019, Figure 5-6) and through photosynthesis convert these nutrients into organic matter for plant structure and growth. This organic matter is available to organisms at higher trophic levels (or further up the food chain) as a source of energy for metabolism and growth. Additionally, the growth of seaweeds adds complexity to the environment by creating three-dimensional habitat. This habitat offers refuge as well as a surface for settlement of other organisms (Langton et al. 2019, Theuerkauff et al. 2021).

Harvesting of seaweeds has the potential to remove significant amounts of nitrogen and phosphorus from estuaries and bays (Barrett et al. 2022, Xiao et al. 2017. Kim et al. 2014, 2015 evaluated nutrient extraction and water quality improvement capabilities by seaweed aquaculture in Connecticut and New York embayments. Two native species in LIS were used - sugar kelp grown over the winter and the bushy red *Gracilaria* alga that grows during the summer. High School students at Bridgeport aquaculture high school and at Rocking the Boat in the Bronx were involved to help grow and harvest the seaweed for the co-authors to estimate nutrient extraction and improving water quality at Hunt's Point, NY and in Fairfield and Branford, CT. Kim and Yarish estimated that if both species were grown in aquaculture operations, using just 1.5 percent of the Sound, 2.2 million kilograms (nearly 5.9 million pounds) could be removed per year. In addition, the seaweeds are effective at removing carbon dioxide, and together could remove about 2,000 kilograms of carbon per hectare (4400 pounds per acre) per year (Van Patten 2015).

Seaweed aquaculture is a primary component of the integrated multi trophic aquaculture (IMTA) system that has been developed to mitigate the waste produced during co-cultivation. Seaweed and shellfish are non-fed aquaculture that are set up with fed aquaculture like fish and shrimps which produce high levels of waste as NH_4 (Figure 5-6 demonstrates fed and non-fed aquaculture diagram, Zhang et al. 2015). IMTA systems and strategies are used often in Asia, with Zhang et al. 2015 using a 3D numerical modeling approach for site selection and design of IMTA systems for bays in Japan. IMTA systems are also being set up in U.S. coastal waters to support farmers with cultivating multiple sustainable resources while mitigating waste (e.g., Barrett et al. 2022, see https://www.greenwave.org/).

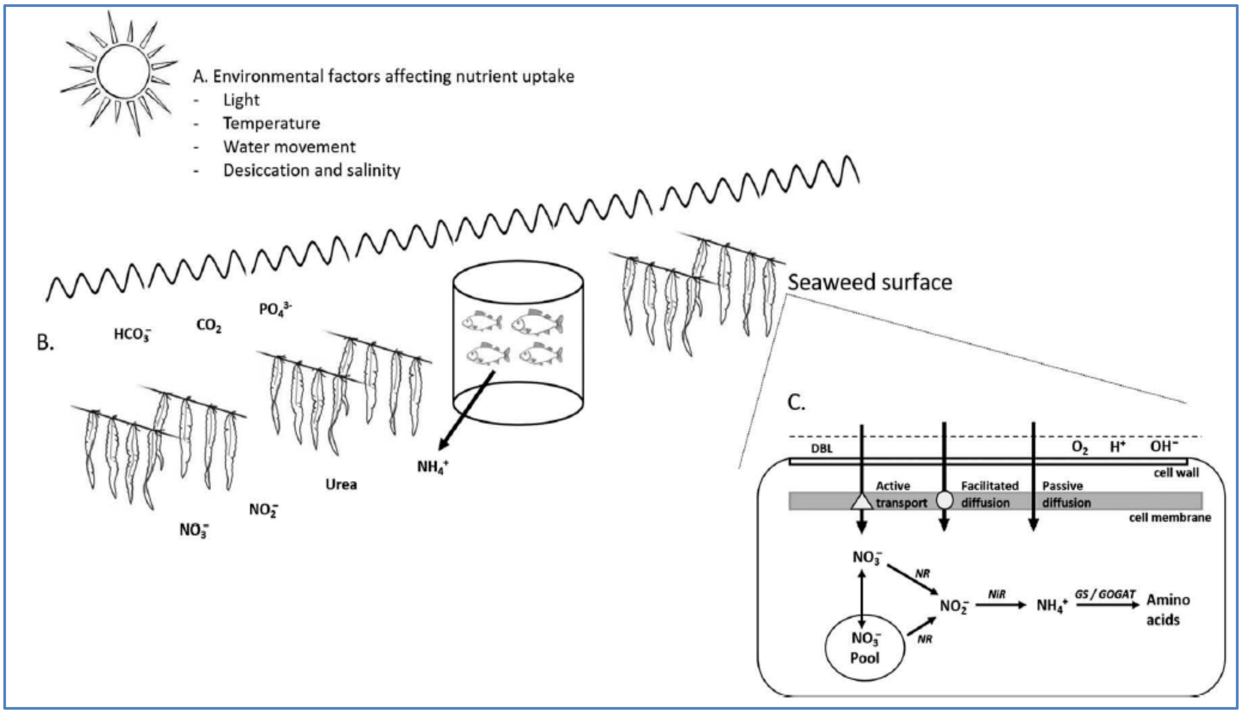

Figure 5-6 Diagram from Roleda and Hurd 2019 showing A. Environmental factors regulating nutrient uptake by seaweeds; B. inorganic carbon, nitrogen and phosphorus sources in water available for seaweed growth, as well as ammonium levels that are enhanced from wild and cultured fish (IMTA); and C. nutrient uptake by seaweeds much cross the diffusion boundary later (DBL) and cell wall. In the DLB, O2, H and OH are released via photosynthesis, respiration and nutrient uptake may accumulate.

5.2 Classifications of Living Resource Models with Example Model Approaches

Based on our literature review and experience, this section provides an overview of generalized living resource modeling approaches that are available or have been applied in LIS and other estuaries. These generalized approaches include index models, biogeochemical models, and biomass or population dynamics models. The review was not meant to be exhaustive but was compiled instead to find commonalities across the various model approaches and to examine the strength/weaknesses of the different approaches, for the purposes of developing a representative short list of applicable models that could be examined in more detail regarding modeled inputs, parameters, processes, and outputs.

5.2.1 Index Models

The most commonly applied index models are habitat suitability index (HSI) models (e.g., USFWS 1981). HSI models describe the suitability or capacity of a given area or region to support a species based on multiple overlapping physical and water quality parameters within the given area. HSIs often encompass the entire life cycle of a species in order to describe suitable habitat or species occurrence based on water quality and physical drivers, but the effects on species vital rates (i.e., survival, growth, reproduction, transport or movement) are implicitly accounted for in simplified suitability functions or indices usually scored between 0.0 and 1.0. There are also index models that estimate species health or condition (e.g., longest leaf length * biomass of eelgrass in Niantic River Estuary (Vaudrey et al. 2019),

Table 5-1), as well as a probability of occurrence based on fitting relationships to presence/absence or areal abundance or biomass, with the environmental measurements. These index models are similar in functional forms, parameterization and inclusion of the same driving environmental variables. Simple governing equations are most often linear or trapezoidal in functional form, but can also be complex curvilinear or peak functions (e.g., see Figure 5-7) from nonparametric statistics.

The benefits of HSI models are that they are often publicly available and widely used. They are easy to construct and test, and they can be validated with observed monitoring data for species occurrence. The index models lack well-defined relationships or feedback with nutrient cycling or water quality since the models are one-way coupled to predict habitat capacity or suitability to support the species, rather than projecting dynamic biomass growth or species processes such as filtration or nutrient uptake. There already exist published and validated habitat suitability models for LIS to help site suitable locations for shellfish and SAV and evaluate their production potential into the future.

SI driver variables commonly included in HSI models for shellfish include area of hard substrate to capture potential areas for larval settlement and available reef areas, and monthly to seasonal salinity to capture conditions necessary for shellfish survival, growth, and reproduction. Some SI relationships have also been developed for bottom dissolved oxygen (DO), or water depth which is sometimes used as a proxy for bottom DO, turbidity or TSS concentrations which can affect shellfish filtration, and/or water flow or Chl-a concentrations to represent food supply or capacity for growth (see Table 5-1).

SI driver variables commonly included in HSI models for SAV include seasonal water temperature and salinity, water levels or depth minimums so that SAV are not exposed, and available light or turbidity measurements during SAV growing season (Table 5-1). Other driving variables that determine SAV suitability or presence, or health are available substrate for SAV rooting and growth, wind or wave forcing which can stress SAV if too forceful and cause erosion, and presence of algal blooms which can shade or prohibit SAV growth (see Table 5-1).

SI driver variables most common to macroalgae or seaweeds include temperature and salinity, light availability, water depth, and current flows which help deliver nutrients that the seaweeds need for photosynthesis (see Table 5-1). Naturally occurring seaweeds need suitable substrate and light availability in the water column, whereas cultured seaweeds are often suspended or hanging on anchor lines so surface temperature and light availability are more important.

There are already state-level GIS-based shellfish aquaculture site selection tools that are based on HSIs under development or in use in LIS for both Connecticut and for New York (see websites at: http://seagrant.uconn.edu/whatwedo/aquaculture/shellmap.php and at http://gis.co.suffolk.ny.us/shellfish/index.html). For example, Bricker et al. 2015 applied the approach from Silva et al. 2011 (see Table 5-1) and combined the Connecticut Aquaculture Mapping Atlas (see Sea Grant UCONN link above) with the local scale Farm Aquaculture Resource Management model (FARM; Ferreira et al., 2007,www.farmscale.org) to create an improved tool for siting culture sites for Eastern oysters in Connecticut coastal waters. Bricker et al. 2015 state that their intent was to improve shellfish siting decision support tools available to growers, resource managers, and regulators by addressing: 1) where shellfish operations can be sited, and 2) determine how well shellfish will grow at the sites deemed suitable.

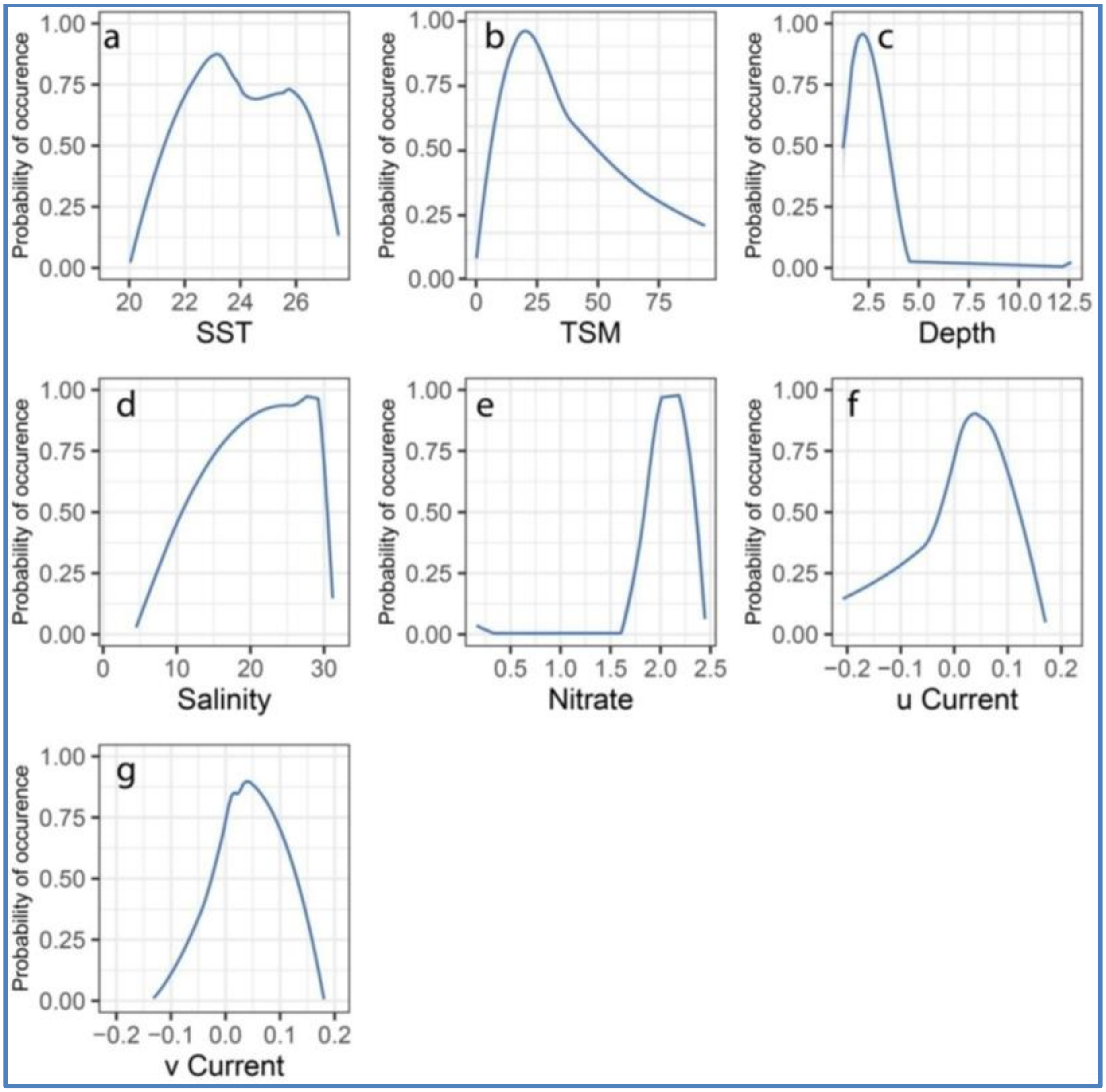

Figure 5-7 Indices from 0.0 to 1.0 from Sarker et al. 2021 showing the GAM (Generalized Additive Model) functions fit to seaweed probability of occurrence data based on environmental variables for the northern Bay of Bengal, Bangladesh. (a) Sea Surface Temperature (SST) (◦C), (b) Total Suspended Matter (TSM), (c) Depth – root cube transformed depth in m, (d) Salinity, (e) Nitrate (μmol/L), (f) surface eastward geostrophic sea water velocity in ms^{-1} (u current) and (g) the meridional component of the absolute geostrophic velocity current in $m\ s^{-1}$ (v current).

Table 5-1 Index Models for SAV, Shellfish, and Seaweed

Example Models	Vaudrey et al. 2013 Eelgrass HSI (EHSI)	Vaudrey et al. 2019 Eelgrass Health Indicator & Presence	Kemp et al. 2004 Eelgrass HSI for Light Availability	Silva et al. 2011 Bricker et al. 2016 Oyster HSI for culture site selection	Sarker et al. 2021 Seaweed GAM
Driving (Independent) Variables:		Other EHI drivers: Annual and spring wind speed		Other drivers: Social & regulatory constraints Current flow	Other drivers: U, V current flows
Water level/depth	Maximum allowable depth band ~7 m for all of LIS	Not in model	Mean tidal level with minimum water depth	4 – 25 m for shellfish culture	Water depth in m
Temperature	Surface Temp in July-Aug	Summer water temp Annual air temp		Water temp at 1-15 m	Bi-weekly SST
Light availability/TSS	% Light at bottom from March-Sept	Fall light levels	Percent light through water (PLW) Percent light at leaves (PLL) TSS affects PLW	TPM (total particulate matter) inhibits filtration	Satellite Total suspended matter (TSM) TSS not in final model but evaluated
Salinity	Not in final model – field data using monthly station data	Not in final model Surface and bottom salinity evaluated		Salinity at 1-15 m	Bi-weekly salinity
N, P, Si, Org-C	Sediment TOC in final model – monthly station data for TDN and TDP evaluated	Not in final model Surface and bottom DIN, DIP evaluated Sediment Organics, DIN, DIP for SAV presence	DIN, DIP affect Chl-a and epiphyte growth and therefore PLW and PLL for SAV	Not in model	Bi-weekly station NO_3
Chl-a	Not in final model – field data from March-Sept	Not in final model Surface and bottom Chl-a evaluated	Chl-a affects PLW	Chl-a, POM for food availability	Not in final model Satellite data evaluated
Substrate/Bottom type	Sediment grain size % Silt & Clay	Substrate, % Silt and Clay for SAV presence	Not in model	Fine mud substrate least impacted by shellfish culture	Not in model
Low DO	Low DO for July-Aug	Not in final model Surface and bottom DO evaluated	Not in model	Low DO inhibits respiration	Not in model

Time step	EHSI set up to describe eelgrass suitability from 2009-2011	Annual eelgrass data; Gauge data averaged by seasons and years	Monthly water quality data since 1985 from CBEMP for evaluating light functions and parameters with SAV presence	Seasonal physical and water quality monitoring data to estimate suitable sites	Seaweed and environmental field data collected twice per month from 2020-2021
Coupling with Hydro-WQ	Monthly field station data from 2009-2011 used to estimate single EHSI across grid cells	N/A - multivariate statistical models using NRE and bay data	N/A	N/A	N/A
Mass balance assumption	No	No	No	No	No
Model Outputs	Weighted HSI score between 0 - 100	SAV Presence/Absence Eelgrass Health Indicator = length of longest leaf * areal SAV biomass	SAV growth with light levels SAV presence to validate light suitability model	Suitability scores between 0 - 1 for culture sites	Seaweed occurrence probability between 0-1
Spatial Evaluation	30-m grid cells set up for maximum allowable depth (m) to create shallow water band around LIS	Three regions in the NRE, Niantic Bay region, and two coves near NRE	SAV presence and water quality monitoring data in Chesapeake Bay	GIS grid cells at 37-m for 110,000 cells covering Chile Pacific coast region	80 sample site locations and satellite data across coast for 2020-2021

Hybrid HSI approaches have also been used. For example, Kemp et al. 2004 presents more complex derivations for SAV habitat requirements based on five driving variables of water quality, light availability, and physical-chemical requirements for Chesapeake Bay. The co-authors describe light as the primary controlling variable for SAV growth, and develop an algorithm for partitioning total attenuation of light (to SAV leaves) into water column and epiphyte contributions. The approach further partitions water column light attenuation into contributions from phytoplankton biomass, inorganic suspended solids, and other substances. This approach, therefore, also uses biogeochemical and dynamic biomass growth modeling in determining habitat suitability for SAV. We include this approach within the index model classification because the co-authors first used target values of minimum or maximum threshold conditions from intensive field studies (Batiuk et al. 1992, Koch et al. 2001, see Table 5-2). The Kemp et al. 2004 formulations for determining light availability for SAV suitability and growth are the common formulations used in most index models for SAV.

Table 5-2 Pasted Table 2 and Table 3 from Kemp et al. 2004 to demonstrate the statistically-derived thresholds that are used to determine suitability or occurrence of SAV. The listed environmental driving variables and the thresholds were summarized from field studies listed within Kemp et al. 2004.

TABLE 2. Statistically-derived water quality thresholds beyond which submerged aquatic vegetation (SAV) are not present, and calculated minimum light requirements for SAV survival.[a]

Salinity Regime[b]	Growing Season[c]	Light Required at SAV Leaf (%), PLL_{min}	Light Required through Water (%), PLW_{min}	Water Column Light Attenuation (K_d, m^{-1})	Total Suspend Solids ($mg\ l^{-1}$)	Plankton Chlorophyll *a* ($\mu g\ l^{-1}$)	Dissolved Inorganic Nitrogen ($mg\ l^{-1}$)	Dissolved Inorganic Phosphorus ($mg\ l^{-1}$)
Tidal Freshwater	April–October	>9	>13	<2	<15	<15	—	<0.02
Oligohaline	April–October	>9	>13	<2	<15	<15	—	<0.02
Mesohaline	April–October	>15	>22	<1.5	<15	<15	<0.15	<0.01
Polyhaline	March–May September–November	>15	>22	<1.5	<15	<15	<0.15	<0.01

TABLE 3. Summary of physical, geological, and chemical factors possibly defining habitat constraints for submerged aquatic vegetation (SAV) (modified from Koch 2001).

Factor	Description	Constraint	Submerged Plants
Water Movement[a]	Minimum velocities ($cm\ s^{-1}$)	0.04–5	Freshwater plants
		3–16	Seagrasses
	Maximum velocities ($cm\ s^{-1}$)	7–50	Freshwater plants
		50–180	Seagrasses
Wave Tolerance[b]	Height < 0.5 m	Limited growth	Canopy-formers (e.g., *M. spicatum*, *R. maritima* reproductive)
	Height < 2 m	Tolerant growth	Meadow formers (e.g., *Z. marina*)
Sediments[c]	Grain size (% silts and clays)	2–62	Freshwater plants
		0.4–72	Seagrasses
	Organic matter (%)	0.4–16	Mixed species
Porewater Sulfide[d]	(mM)	<1	Healthy plants
		>1	Reduced growth
		>2	Death

Vaudrey et al. 2013 constructed an eelgrass HSI (EHSI) that projected the sum of weighted parameters for the shallower waters of LIS using GIS and available field monitoring data. Vaudrey et al. 2013 first removed all deeper waters where light reaching the bottom is 2% or less in the GIS-based analysis for LIS. After removing all deeper waters with poor light for SAV growth, water clarity as percent of light reaching the bottom, total nitrogen, total phosphorus, sediment grain size (% silt & clay), sediment organic content, maximum water temperature, chlorophyll *a*, total suspended solids, pH, and salinity were evaluated for SAV. The final five parameters chosen for inclusion in the model included percent light to the bottom, temperature, dissolved oxygen, sediment grain size as % silt & clay, and sediment organic content (Table 5-1) to remove cross-correlation among the field =data for determining suitability (e.g., Chl-a concentration and light availability). Vaudrey et al. 2019 determined a health indicator using areal biomass of SAV and the length of the longest leaf for eelgrass in the Niantic River Estuary (NRE) and other Connecticut embayments. Multivariate approaches were used to determine which environmental field monitoring data best described the variation in annual eelgrass health indicators for 30 years of record in the NRE. The dominant drivers of eelgrass health in the NRE are summer air temperature and annual water temperature. Significant secondary drivers on eelgrass health included average annual wind speed and fall sunlight, which was correlated to warmer temperatures being detrimental to seagrass health (Table 5-1).

Habitat suitability or occurrence modeling for determining suitable areas for seaweed culture have been applied to large coastal regions covering, or else for regions in the open ocean, as a tool for countries to determine seaweed production (Chen 2019) and expand mariculture (Sarker et al. 2021). Whereas Chen 2019 used Bayesian statistics to determine what environmental variables explained seaweed production for Japan, Sarker et al. 2021 used a generalized additive model (GAM) approach for predicting seaweed probability of occurrence off the coast in Bangladesh (Figure 5-7, Table 5-1) based on eight explanatory variables measured in the ocean waters including salinity, NO_3, PAR, depth and ocean currents.

5.2.2 Nutrient Cycling and Biogeochemical Models with Living Resources

Most of the summary descriptions for biogeochemical models are adapted from synthesis and reviews of freshwater and coastal-marine biogeochemical models. Reviews include Ismail and Al-Shehhi (2022) and earlier reviews of aquatic biogeochemical models (Franks, 2002; Arhonditsis and Brett, 2004; and Ganju et al., 2016). These literature resources provide excellent details related to aquatic biogeochemical modeling including descriptions of various levels of complexity and coupling of biogeochemical models with surface water hydrodynamic models including ocean circulation models.

Mechanistic biogeochemical models of coastal waters are used to quantify numerous aspects of process-oriented plankton ecosystem models including primary productivity, cycling of nutrients, redistribution of plankton, and variability of the carbon cycle. Water quality and biogeochemical models are typically linked to hydrodynamic models with horizontal grid resolution ranging from 10-100 m for fine-scale embayments to 100 m - 5 kilometers for coastal systems (e.g., Long Island Sound) and 1 - 50 km for the Middle Atlantic Bight. Vertical resolution can range from a simplified 3-layer model characterized by vertical salinity, water temperature, and density structure as (1) well-mixed surface euphotic layer; (2) pycnocline layer where vertical mixing is minimal because of stratification; and (3) sub-pycnocline layer that extends from the bottom of the pycnocline to the seabed with ~10 -50 vertical layers to account for stratification and vertical mixing. Most ocean circulation models (e.g., ROMS, ECOMSED, EFDC) used for continental shelf applications use a terrain - following sigma-coordinate scheme where a fixed number of layers (e.g., 10) are distributed over the total water column depth and the thickness of each layer can be “stretched” to better resolve near-surface and near-bottom layers.

The earliest biogeochemical models of coastal – marine systems began with the pioneering mechanistic, process-oriented model of nutrients, phytoplankton and zooplankton using data collected in Georges Bank (Riley et al., 1949). During the 1960’s – 1980’s, Riley’s influence continued with development of eutrophication models for estuarine (Di Toro et al., 1971), upwelling systems (Walsh and Dugdale, 1971), the North Sea (Steele, 1974) and the continental shelf of the Middle Atlantic Bight (Walsh et al., 1987). The classical NPZD approach was developed by Fasham et al. (1990) where NPZD refers to “Nutrients, Phytoplankton, Zooplankton, and Detritus”. The four main compartments can be categorized into biotic (e.g. phytoplankton, zooplankton, fishes, whales) and abiotic (e.g., ammonium, nitrate, dissolved organic/inorganic carbon, particulate organic carbon). As for biota, phytoplankton and zooplankton are the core state variables where phytoplankton are autotrophic and obtain their energy from sunlight and can fix the carbon dioxide, and zooplankton are heterotrophic organisms obtaining their energy by consuming other organisms. For the abiotic components, in addition to what was mentioned above, biogeochemical models also consider nitrogen as the main limiting nutrient in ocean and coastal regions which is primarily in the form of Dissolved Inorganic Nitrogen (DIN). The other important limiting elements included in biogeochemical models that are also considered include orthophosphate, iron and silicate. The representation of these biotic and abiotic compartments is governed by one or more mass balance-based state variables which can be used to define water quality constituents and trophic levels of the pelagic ecosystem.

Biochemical parameters have been studied in various ecosystems using different types of biogeochemical models, these parameters include chlorophyll-a, macronutrients with are the primary limiting nutrients for phytoplankton growth (nitrate, phosphate, silicate), micronutrients (Fe), carbon and oxygen cycles (Ismail and Al-Sherri 2022). Chlorophyll-a is usually used as a metric of biomass concentration instead of carbon biomass due to its unique optical properties and it is one of the widely studied parameter in the biogeochemical modelling. The level of this parameter is affected by several basic factors including solar irradiance penetrating the water column, dissolved nutrients depth, and temperature (Sverdrup, 1953; Wroblewski et al., 1988). Although the chlorophyll-a to carbon and nutrient ratio (Chl: C: nutrient) can be highly variable due to an acclimatize response to changes in environmental conditions such as irradiance, temperature, and nutrient availability, this flexibility is often neglected in large-scale biogeochemical models.

There are several examples of biogeochemical models in the literature for LIS and similar systems that include the effects of shellfish filtration on POM concentrations in the water column (e.g., phytoplankton or Chl-a), and SAV and seaweed uptake of DIN and DIP, and CO_2 for photosynthesis, along with storage or sequestration of C or N by the living resources for structural maintenance (see Table 5-3). The models described below are included within the biogeochemical framework specifically for evaluating effects on nutrient cycling due to eutrophication or nutrient loading scenarios, and include effects on living resources. Some of the models simulate dynamic biomasses of the living resources changing with the conditions via 2-way coupling within the biogeochemical or ecosystem model (see Table 5-3, e.g., Bricker et al. 2018, Vaudrey et al. 2020, Buzzelli et al. 1998, Brush and Nixon 2009). The other modeling study assumed fixed biomass of the living resources within the biogeochemical model framework (Table 5-3, Miller and Wands 2009).

Table 5-3 Biogeochemical Models that include SAV, Shellfish, or Seaweeds

Example Models	Buzzelli et al. 1998 Seagrass Biomass	Vaudrey et al. 2020 Eelgrass Biomass	Bricker et al. 2015, 2018 Shellfish Biomass	Miller and Wands 2009 Shellfish Biomass	Miller and Wands 2009 Seaweed Biomass	Brush and Nixon 2010 Seaweed Biomass
Driving (Independent) Variables:		Other driving inputs: winds, freshwater flushing				
Water level/depth	Daily water depth for subtidal habitat boxes	Not in model	Hourly water level modeled by Hydro model	Hourly water level modeled by Hydro	←	Average water depth for seven spatial boxes in estuary
Temperature	Daily water temperature	Average daily temperature	Hourly temperature by Hydro-SWEM	Hourly temperature by Hydro-SWEM	←	Average daily water temperature
Light availability/TSS	Average annual PAR with shading by leaf for SAV, to bottom for benthic algae	Average daily surface PAR with light absorption by phytoplankton, macroalgae, Zostera	Daily surface PAR and photoperiod for SWEM	Daily surface PAR and photoperiod for SWEM	←	Daily surface PAR with photoperiod and photic depth, light absorption by phytoplankton, macroalgae for three of seven spatial boxes
Salinity	Not in model	State variable in the EcoGEM biogeochemical model	Hourly salinity by SWEM	Not in model	←	Not in model
N, P, Si, Org-C	State variables for labile and refractory detrital particulate organic carbon (LPOC and RPOC), DOC, DIN	State variables for nitrogen, phosphorus, benthic carbon, and oxygen	State variables for N, P, DO can be calculated by EWN, but SWEM used to generate these variables as inputs to EWN boxes	State variables in SWEM are DO, as five phosphorus, six nitrogen, two silica and six organic carbon forms	←	State variables for N, P, C, DO in water column and bottom layer/sediments
Chl-a	State variables for diatoms and other phytoplankton, sediment macroalgae	See below	State variables for phytoplankton biomass (POM, Chl-a) by SWEM to EWN boxes	State variables for diatoms and flagellates by SWEM	←	C, N, P state variables for phytoplankton biomass in g m^{-2}
State Variables	C and N state variables for Zostera marina shoots (ZS), root-rhizomes	C and N state variables for phytoplankton,	Oyster biomass based on individual growth and mortality for 20 oyster weight classes	Bivalve carbon biomass (g C m^{-2}) is fixed per cell based on maximum shellfish density with	Seaweed carbon biomass (g C m^{-2}) is fixed to maximum near-bottom and	C, N, P state variables for *Ulva* and *Gracilaria* biomass in g m^{-2} dependent on

	(ZRR), and epiphytes (Zepi); *Spartina alterniflo-ra* shoot and root-rhizomes (SS and SRR)	macroalgae, and *Zostera* biomass		temperature-dependent clearance rates from Powell et al. 1992 empirical model	longline seaweed aquaculture densities in a subset of selected cells suited for seaweed aquaculture based on water depth and high DIN	temperature, nutrient concentrations, and light availability in three shallow spatial boxes of estuary model
Time step	Hourly time step run over multiple years	Daily time step run over multiple years	Hourly hydrodynamics and nutrients in SWEM with daily oyster biomass over a year and then decades with EWN	Hourly hydro and biogeochemical cycling with shellfish filtration effects over days within year	←	Daily time step run for a year
Coupling with Hydro-WQ	Monthly field station data from 2009-2011 used to estimate single EHSI across grid cells	3D box model for hydrodynamics and mixing with EcoGEM	3D SWEM drives hourly temp, salinity, N, P, DO, Chl-a and POM to EWN boxes	Coupled Hydro-SWEM with fixed shellfish biomass by SWEM cells	←	None for this study of the ecosystem box models set up with field data
Mass balance assumption	Yes - via biogeochemical cycling in four spatial boxes	Yes - via biomass growth and biogeochemical cycling in three spatial boxes	Yes - via oyster biomass growth, filtration and biogeochemical cycling in 42 EWN spatial boxes	Yes, for SWEM, but shellfish remove nutrients and carbon but biomass is fixed	←	Yes – via biomass and biogeochemical cycling in seven spatial boxes
Model Outputs	Daily C, N, Zostera shoots (ZS), root-rhizomes (ZRR) epiphytes (Zepi); *Spartina* shoot and root-rhizomes (SS and SRR)	Daily to seasonal C, N, P, DO, phytoplankton, macroalgae, and *Zostera* biomass	Oyster production, Chl-a, POM, N via transport, biogeochemistry, and shellfish filtration	Daily DO, P, N, Si and Org-C, diatoms and flagellates from SWEM over the year	←	Daily C, N, P in g m^{-2} for phytoplankton, *Ulva* and *Gracilaria* biomass pools
Spatial Evaluation	Four habitat spatial boxes for Sand, *Zostera*, Intertidal mud, Intertidal Marsh	Three spatial boxes for NRE based on salinity and mixing in estuary	2300 SWEM spatial boxes with 10 vertical sigma layers; 42 EWN spatial boxes with 2 vertical sigma layers	2300 SWEM spatial boxes with shellfish filtration modeled in cells with fixed biomass based on shellfish aquaculture	2300 SWEM spatial boxes with seaweed nutrient removal and DO in cells with fixed biomass based on aquaculture	Seven spatial boxes for Greenwich Bay in Upper Narragansett based on depth, salinity and mixing in estuary

Bricker et al. 2015, 2018 used a framework that set shellfish grounds within the EcoWin.net (EWN) spatial model coupled to the 3D SWEM for system-scale model evaluation of shellfish bio-extraction potential for LIS (Table 5-3). The EWN ecological modeling package is an object-oriented framework designed to simulate key components of biogeochemical cycles, including processes in the water column and sediments. It targets specific issues of relevance to integrated coastal zone management, including eutrophication and aquaculture (Ferreira 1995). EWN is box model, where all conditions are considered to be homogeneous within the 42 spatial boxes and 2 vertical sigma layers. Size-based clam and individual-based oyster filtration and clearance rates dependent on temperature in the EWN remove phytoplankton (POM, Chl-a). While the EWN model itself calculates concentrations of nutrients, algal biomass, and dissolved oxygen, SWEM values for temperature, salinity, algal biomass, and nutrient and DO concentrations were provided as time-weighted averages to further inform the EWN for estimating oyster filtration by spatial boxes and for the system-scale.

Vaudrey et al. (2020) have a report describing ongoing work using a somewhat similar box model to that of EWN that they have named NREEM (Niantic River Estuary Ecosystem Model) with biogeochemical cycling in three spatial boxes defined by salinity and nutrient loads for the NRE, and with simulated effects of light availability, temperature, and nutrient uptake by phytoplankton, epiphytic algae, and eelgrass to estimate daily biomass (Table 5-3). The NREEM output consists of averaged daily estimates of state variables and rates associated with these changes for each spatial box. The state variables are salinity, dissolved oxygen, phytoplankton biomass, seagrass biomass, macroalgal epiphytic biomass, water column nitrogen, water column phosphorus, and benthic carbon (Vaudrey et al. 2020). Vaudrey et al. 2020 uses empirical data collected over 30 years and previously used to determine seagrass for the NRE (Vaudrey et al. 2019) to help parameterize the temperature, light, and nutrient effects on the phytoplankton, macroalgae and seagrass biomass from earlier biogeochemical modeling of seaweeds (see Brush and Nixon, 2010 also in Table 5-3). The report concentrates on model description and development, there are no biomass results for the phytoplankton, epiphytic algae, or seagrass within the report, however the model selection, set up and design suggests that this NREEM model will be used for evaluating the coupled effects of seagrass production (daily biomass changes) with nutrient cycling (i.e., nutrient loading, eutrophication, removal strategies).

Buzzelli et al. (1998) included an eelgrass habitat module within a biogeochemical framework that included four spatial habitats – subtidal sand, subtidal seagrass (eelgrass), intertidal mud flat, intertidal marsh – for a NERR (National Estuarine Research Reserve) on Goodwin Islands in Chesapeake Bay (Figure 5-8). Each spatial habitat box is driven by surface light (PAR), temperature, and tidal water level to simulate daily biogeochemical cycling in order to estimate the potential ecological responses to eutrophication scenarios in the littoral zone (see Table 5-3). The Buzzelli et al. (1998) daily growth equations and parameterization for phytoplankton size classes, epiphytic algae, eelgrass, and benthic algae are similar in form and function to those used by Brush and Nixon 2010 and Vaudrey et al. 2020 within their respective biogeochemical or ecosystem modeling frameworks (see Table 5-3). Buzzelli et al. (1998) showed that daily eelgrass biomass was regulated by the interactive effects of light, nitrogen and grazing on epiphyte growth. They showed that increased eelgrass biomass in the littoral zone predicted doubling of ecosystem production, however it reduced the production of planktonic and sediment microalgae.

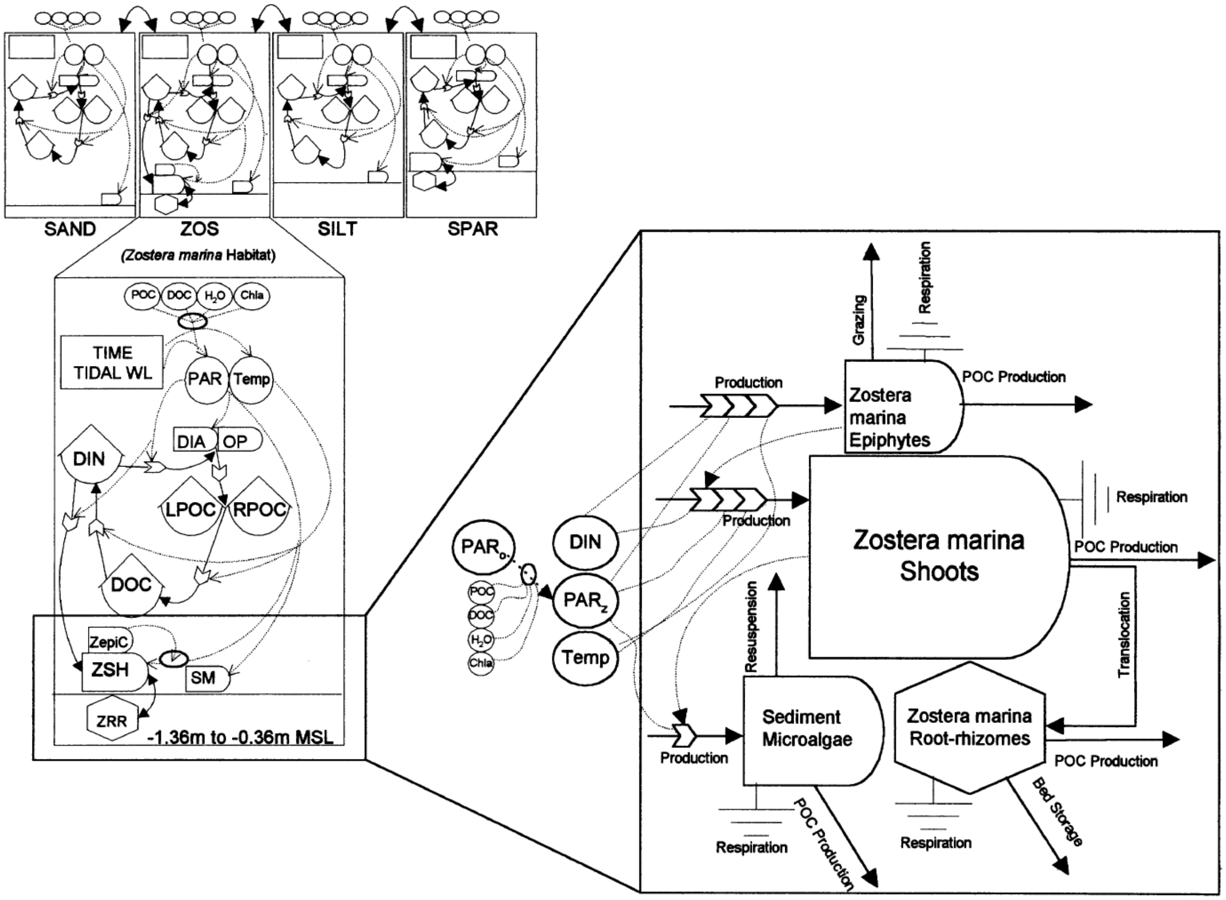

Figure 5-8 Eelgrass habitat and community conceptual diagram from Figure 2 in Buzzelli et al. 1998. Conceptual diagram is included to show the four spatial habitat boxes (top), with the nutrient state variables of the biogeochemistry model within the habitat box (left), with the drivers that affect the eelgrass community biomass (large box on right).

Biogeochemical models have also been used to assess the potential effects and consequences of bioextraction as a management tool in LIS. For example, HydroQual did a preliminary assessment of nutrient removal potential by shellfish using *Rangia* filtration rates from Powell et al. 1992 from Chesapeake Bay to simulate shellfish filtration, assimilation and removal through harvest within the SWEM cells for LIS (Miller and Wands 2009, see Table 5-3). The application used 500 g C m^{-2} maximum biomass for shellfish farms or leases within the SWEM biogeochemical framework simulating four Phosphorus forms, six Nitrogen forms, two phytoplankton taxa, C, and DO to measure nutrient removal potential by the shellfish farms. The work is similar to earlier work done by Cerco and Noel 2007, 2010 (see Table 5-3) as HydroQual was involved in the CBEMP.

Miller and Wands (2009) also simulated kelp effects on nutrient cycling with SWEM. SWEM includes inputs of time variable inorganic nutrient loss rates due to seaweed at various locations based on user-specified seaweed density and seaweed nutrient stoichiometry. Kinetics were developed in SWEM for calculating nutrient extraction rates per grid cell based upon the defined seaweed densities in mass per area units. By multiplying by depth, these densities were converted to mass seaweed per volume units. Self-shading effects of the biomass were also included in the SWEM calculations. Light attenuation beneath seaweed/kelp farms was increased in SWEM to mimic the shading effects of the seaweed and the reduction in light available for phytoplankton.

SWEM simulations were performed with the fixed biomass of shellfish and kelp farms within the SWEM grid to assess nutrient removal based on shellfish and kelp farm placement (e.g., near bottom v. photic zone, kelp farms near or far from approved waters for shellfish). Model sensitivity to shellfish assimilation efficiency and density were examined. The co-authors pointed out that an important consequence of the seaweed nutrient removal that SWEM captures mechanistically is that less nutrients are available to fuel phytoplankton growth as a result of the competing seaweed/kelp uptake of dissolved inorganic nutrients and removal of seaweed/kelp and absorbed nutrients, and offered the recommendation that seaweed/kelp farms be placed at the edges of the Sound to intercept dissolved inorganic nutrients before they can reach phytoplankton in the main open waters (Miller and Wands 2009).

5.2.3 Dynamic Growth or Population Biomass Models

Dynamic growth or population biomass models use equations to represent the rates of change of the abundances or biomass of the species. These models are formulated to assess how changes in environmental conditions affect species growth, survival, and reproductive processes (sometimes movement or transport, too) to ultimately affect abundance or biomass over time. Dynamic growth models can also be applied at the individual level to describe the energetics or energy budget for somatic growth and reproduction of an organism. These individual growth models are usually scaled up to represent the greater biomass or population for a defined area or culture site at a local scale, or by a region or water body if the population is being evaluated at a system-scale.

The dynamic growth or population biomass models also assume mass balance for the species growth or biomass over time, and often use species rates and processes much like the biogeochemical models in Section 5.2.2. There is some overlap between the model approaches and example studies for LIS and similar systems in the two sections. We have separated the model approaches based primarily on how the living resource models were originally developed to evaluate the living resources.

There are examples of dynamic shellfish growth and biomass models for the LIS and similar systems (see Table 5-4). Cerco and Noel (2005, 2007, 2010) applied dynamic biomass models to eastern oysters and mussels within the mass-balance framework of the Chesapeake Bay Environmental Model Package (CBEMP). This work was undertaken over a decade to evaluate filtration effects on phytoplankton concentrations, DO, nutrient cycling, and SAV biomass. The mass balance biomass equations for the eastern oysters and mussel species within Chesapeake Bay depend on filtration rates that are modified by temperature, salinity, TSS, DO. Species-specific assimilation and basal metabolic rates are additionally modified by temperature. The shellfish assimilate C, DIN and DIP over time for biomass growth, use DO for respiration, and release DIN, DIP and POM back into the CBEMP via excretion and bio-deposition (see Table 5-4).

Table 5-4 Dynamic Growth or Population Biomass Models of SAV, Shellfish, and Seaweeds

Example Models	Cerco and Moore 2001 SAV Biomass coupled to CBEMP	Jin and Ji 2013 SAV Biomass coupled to LOEM	Kalra et al. 2020 SAV Biomass in COAWST	Cerco and Noel 2005, 2007 Oyster Biomass in CBEMP	Bricker et al. 2015, 2018 FARM: Coupled physical-biogeochemical-shellfish growth/production model
Driving (Independent) Variables:				Other variables: Historical oyster areas and densities initialize oyster biomass for bars in CE-QUAL-ICM cells	Other variables: Cultivation area in m^2 defined by length and width of each FARM-scale model
Water level/depth	Band of cells in CBEMP between 1-2-m for placing and coupling SAV biomass unit model	Band of cells in 3D LOEM model between 1-2-m for placing and coupling SAV biomass unit model	Generated and used within the coupled ROMS-SWAN-BGCM framework of COAWST	Not used for Oyster biomass modeling	Farm section depth to define FARM-scale volume
Temperature	Generated by CBEMP at 15-minutes	Generated by LOEM at timesteps less than day	Generated and used within the coupled ROMS-SWAN-BGCM framework of COAWST	Generated from CH3D-WES Hydro model	Daily T at FARM-scale
Light availability/TSS	Generated by CBEMP at 15-minutes based on surface PAR, depth, light extinction, then absorption by macrophyte and SAV in the coupled cells	Generated by LOEM based on surface PAR, depth, light extinction, absorption by phytoplankton, macrophyte, SAV	Generated by COAWST based on surface PAR, depth, light extinction, absorption by phytoplankton, macrophyte an SAV	Generated from CE-QUAL-ICM eutrophication model	Not in model
Salinity	Not in model but used to initially define modeled regions from the 2100 CBEMP cells in larger domain	Not included in SAV model	In COAWST – ROMS model but not used in SAV biomass modeling	Generated from CE-QUAL-ICM	Daily S at FARM-Scale
N, P, Si, Org-C	Nutrient inputs and state variables for N, P, C forms in CBEMP eutrophication model	Nutrient inputs and state variables for N, P, C, DO forms in LOEM and SAV model	State variables from coupled BGCM model include nutrient, phytoplankton, zooplankton and detritus in mmol N m^{-2}	State variables from CE-QUAL-ICM	POM, TPM state variables estimated by farm zones (multiple zones in FARM section)
Chl-a	Chl-a and phytoplankton biomass are state variables within CBEMP eutrophication model	Chl-a and phytoplankton biomass are state variables in LOEM	Chl-a and phytoplankton biomass are state variables in BGCM	POC state variable from CE-QUAL-ICM	Chl-a state variable by farm zones

State Variables	*Zostera*, *Ruppia*, Freshwater shoot and root biomass g C m^{-2}, epiphyte and phytoplankton biomass in g C m^{-2} by CBEMP cells	SAV shoot and root biomass in g m^{-2}	SAV shoot and root biomass, epiphyte biomass, phytoplankton biomass in g C m^{-2}; SAV shoot density and height	Temp and oxygen-dependent shellfish biomass via filtration rate, excretion rate, assimilation rate, growth rate, respiration rate, predation rate, and hypoxia mortality rate	
Low DO	Not in model	DO state variable produced in SAV model with nutrient cycling	State variable in BGCM and SAV model	DO is state variable from CE-QUAL-ICM	DO is state variable in FARM
Time step	15-minute integration with 10-day output intervals for 10 years	Daily SAV model biomass over 10 years	Fully coupled for less than day time step in model framework to output daily to seasonal SAV biomass, shoot density and height	Daily for oyster biomass	Daily for shellfish growth
Coupling with Hydro-WQ	SAV biomass unit model coupled one-way in CBEMP cells at 1-2-m depth for littoral zone	SAV biomass unit model coupled two-way with DO in LOEM cells at 1-2-m depth for littoral zone	Fully two-way coupled Hydro-WQ-BGCM-SAV and macrophyte biomass for water column and sediments	POC, TSS, and S affect oyster filtration; T affects filtration and respiration; DO affects filtration and mortality	FARM is standalone physical-biogeochemical-shellfish growth/production model Chl-a, POM, S, T affect filtration; DO affects mortality
Mass balance assumption	Yes, via phytoplankton, macrophyte and SAV growth (shoot and root balanced) by CBEMP cell depending on nutrients and light availability	Yes, via phytoplankton, macrophyte, and SAV shoot and root growth depending on nutrients and light by cell, DO coupling added by cell	Yes, via all 2-way coupled Hydro-WQ-BGCM-SAV including SAV bed impacts on waves, drag and mixing	Yes - Oyster filtration and deposition in daily nutrient cycling; and via oyster biomass growth model, in CE-QUAL-ICM cells	Yes – Oyster filtration, excretion, deposition affect Chl-a, POM, N, DO by zones; and via shellfish production at FARM-scale
Model Outputs	*Ruppia*, Freshwater shoot and root biomass in g C m^{-2}, epiphyte and phytoplankton biomass in g C m^{-2} by CBEMP cells	SAV shoot and root biomass, epiphyte and phytoplankton biomass in g m^{-2} by LOEM cells	Daily to seasonal SAV, Chl-a, phytoplankton, and macrophyte biomass, shoot density and height of SAV beds affect water flow and transport	Daily oyster biomass (g C m^{-2})	Monthly shellfish size, biomass by zones at FARM-scale over culture cycle

Spatial Evaluation	CBEMP cells at 1-2-m depth for SAV biomass to evaluate system-wide productivity and differences in SAV cells	LOEM cells at 1-2-m depth for SAV biomass to evaluate system-wide productivity and differences in SAV cells	ROMS curvilinear grid resolution of 100-m for 90 x 98 horizontal cells and 10 sigma layers	Estimate spatial and temporal effects of oyster filtration and deposition on POC, Chl-a, DO, N across Chesapeake Bay	Estimate annual shellfish production and effects on Chl-a, N, DO at FARM-scale Estimate annual N removal at the FARM-scale for 14 tidal rivers/bays (Rose et al. 2015)

Dynamic Growth or Population Biomass Models of SAV, Shellfish, and Seaweeds (continued)

Example Models	Filgueira et al. 2014, 2015 DEB Oyster and Mussel Growth coupled with Hydro-Biogeochemical Model	Broch and Slagstad 2012 Broch et al. 2019 Individual-Based Kelp Growth model coupled to SINMOD
Driving (Independent) Variables:	Other driving inputs: Current velocities (x, y) generated by RMA model used to couple NPZD and oyster, mussel DEB	Other driving inputs: current speed from hydrodynamic model affects transfer among SINMOD biogeochemical compartments and kelp growth
Water level/depth	Generated by RMA hydrodynamic model and used to couple NPZD model with shellfish DEB	Kelp initialized for all grid cells from surface down to 8-m depth
Temperature	Generated daily by RMA model	Daily temperature
Light availability/TSS	Not in model	Daily light availability by depth for SINMOD and kelp growth
Salinity	Not in model	Daily salinity below 25 ppt can inhibit kelp growth
N, P, Si, Org-C	Phytoplankton (P), Nutrients (N), Oyster (O) and Detritus (D) are state variables in biogeochemical model	NO_3 and NO_{4+} concentrations for kelp growth
Chl-a	Generated daily by NPZD model	Not in model
State Variables	Daily NPZD in mg C m^{-3} (nutrients in mg N m^{-3}) Daily oyster size, biomass, and filtration potential in mg C m^{-3} based on somatic growth rate and reproductive growth rate affected by temperature and Chl-a concentrations	Frond area in cm^2, internal nitrogen reserves in g N (g structural mass)$^{-1}$) and carbon reserves in g C (g structural mass)$^{-1}$) in kelp IBM

Low DO	Not in model	Not in model
Time step	Oyster DEB runs on daily time step to project oyster lengths, biomass, and filtration capacity of Chl-a over seasons, years	Kelp IBM runs on hourly time step to project daily kelp growth, C and N reserves over multiple years
Coupling with Hydro-WQ	Oyster DEB one-way coupled with RMA and NPZD model of estuary	Kelp IBM 2-way coupled in SINMOD; SINMOD one-way coupled with coastal ocean model
Mass balance assumption	Oyster DEB growth assumes mass balance; NPZD assumes mass balance concentrations and cycling by spatial zone	Kelp IBM in SINMOD assumes mass balance for kelp growth and C, N reserves
Model Outputs	Oyster shell size, oyster biomass, phytoplankton biomass concentrations in mg C m^{-3}	Kelp frond area, g N and g C in kelp reserves; kelp biomass and composition
Spatial Evaluation	2D RMA model coupled with NPZD model for three spatial boxes in the estuary, with an oyster DEB point model for each spatial box	Coastal ocean model used for depth layers, currents and transport for the Nordic Seas domain with four 800-m resolution SINMOD compartments set up for Norwegian Coast, and three 160-m compartments for cultivation sites

Bricker et al. 2015, 2018 applied the Farm Aquaculture Resource Management (FARM) model to Long Island Sound to evaluate the effects of oyster filtration on eutrophication. Although Bricker et al. 2015, 2018 describe the development and application of a larger coupled model framework used for both local-scale and system-wide analysis of oyster filtration on LIS, the FARM model is included as a dynamic oyster growth and farm-scale production model in this section. The FARM model is a local scale model that combines physical and biogeochemical models, shellfish growth models, and screening models at the farm scale for the determination of shellfish production and for the assessment of water-quality changes on account of shellfish cultivation (See Figure 5-9 and Figure 5-10, Ferreira et al. 2007, 2009, 2012). The table of model inputs and outputs for the shellfish FARM model is pasted from Bricker et al. 2018 below (Table 5-5). The modeled output of interest evaluated in Bricker et al. 2018 was the time for an Eastern oyster to reach harvestable size (i.e. three inches, 7.62 cm) from a seed of one-inch length (2.54 cm). Phytoplankton filtration and removal of nitrogen from the FARM models are estimated locally by year or culture cycle and scaled up and across multiple FARMs for regional or system-wide analysis. Nitrogen reduction by shellfish filtration has been evaluated using similar coupled approaches to that described by Bricker et al. 2018 for LIS in many other coastal systems (Rose et al. 2014, Dvarskas et al. 2020, Holbach et al. 2020, Parker and Bricker 2020, Bricker et al. 2020).

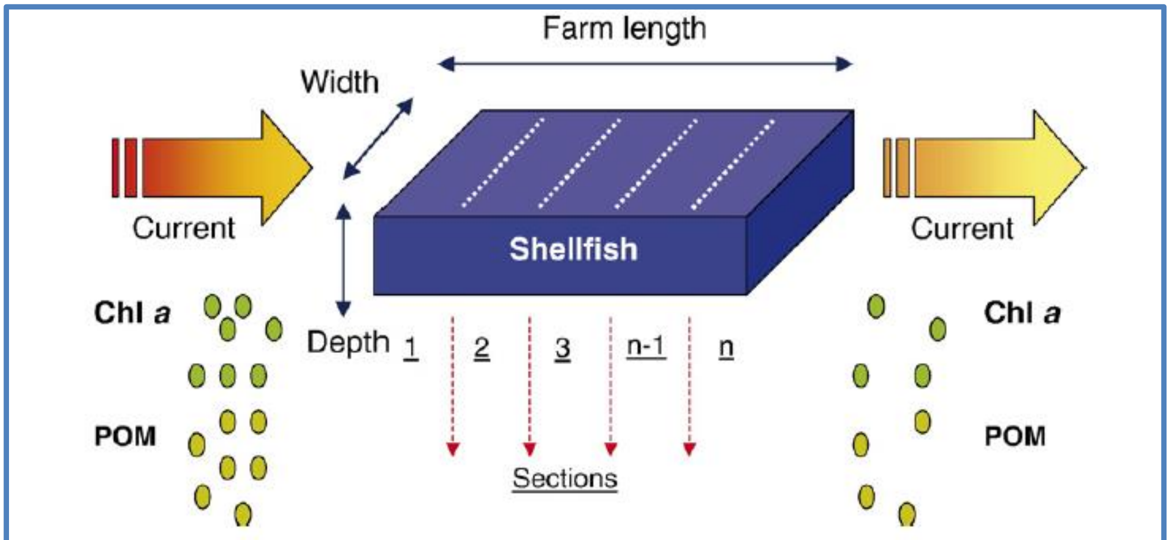

Fig. 1. Farm layout (rope and bottom culture).

Figure 5-9 From Ferreira et al. 2007 describing the FARM model layout for shellfish.

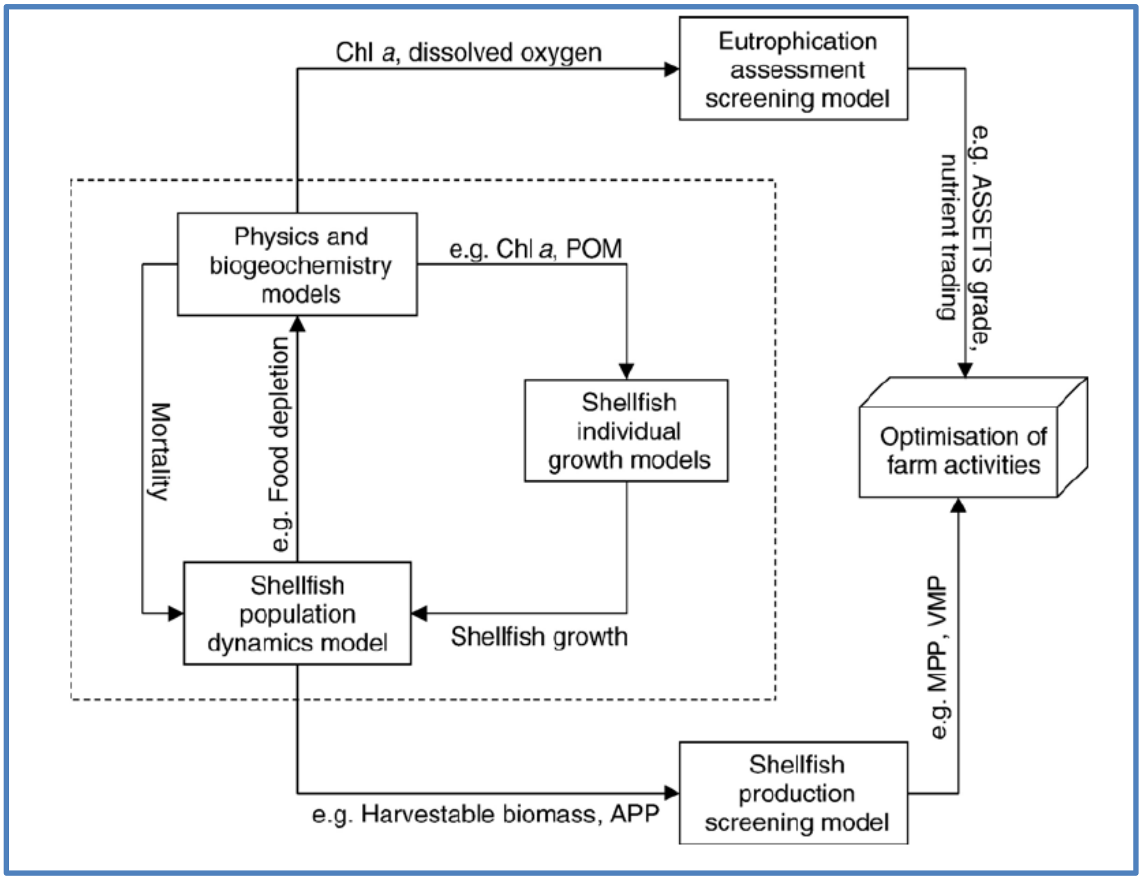

Figure 5-10 Conceptual scheme from Ferreira et al. 2007 showing components of FARM shellfish model. The core model is within the dotted box, the screening models are outside of the box

Table 5-5 Snipped from Table 2 in Bricker et al. 2018 listing the required inputs and model outputs from FARM.

Farm model inputs		Farm model outputs
Farm layout:	*Environment*:	Weight (g)
Farm width	Water temperature	Length (cm)
Farm length	Salinity	Harvest (tonnes)
Farm depth	Current speed	Concentration (upstream, within and downstream of farm):
Number of sections	Wind speed	Chl
Section volume	Concentration:	POM
Total animals	Chlorophyll *a* (Chl)	TPM
Shellfish cultivation:	Particulate Organic Matter (POM)	DO
Species	Total Particulate Matter (TPM)	DIN
Cultivation period	Dissolved Oxygen (DO)	Total Physical Product (TPP)
Stocking density	Dissolved Inorganic Nitrogen (DIN)	Average Physical Product (APP)
Population	*Water Quality data inputs ideally at least once per month*	Total revenue (TR)
		Total carbon (TC)
		Profit
		Time to market size

The Dynamic Energy Budget (DEB) model has been used for simulating daily growth and production of multiple shellfish species in coastal estuaries (Filgueira et al. 2013, 2014, Lavaud et al. 2017, 2021). The DEB describes the individual in terms of three state variables: reserve(s), structure(s), and maturity/reproduction. The energy assimilated from food is stored as reserves; a fixed fraction of this energy is directed towards maintenance and growth of the structural body, and the remainder is directed towards maturation, gamete production and/or maintenance of the reproductive system depending on the life cycle stage of the organism. The DEB model is a popular approach for shellfish because its predicted daily outputs for shell length and tissue mass can be calibrated and validated with field monitoring data (e.g., Lavaud et al. 2017). The shellfish DEB models have been coupled with hydrodynamic and eutrophication models for estuaries to evaluate the potential success of candidate farm locations in terms of biological production as well as ecological carrying capacity (e.g. Filgueira et al., 2013 and 2014, see Table 5-4). Filgueira et al. describe ecological carrying capacity as the maximum stocking or farm density that is possible without unacceptable ecological impacts to the surrounding system (Inglis et al., 2000). Potential production, socioeconomic outputs, and environmental effects can be estimated through application of the DEB models, including future scenarios, in similar ways to how the FARM models have been applied (e.g., Rose et al. 2014, Bricker et al. 2018).

Cerco and Moore 2001 developed a predictive model of three dominant SAV – *Zostera* (eelgrass), *Ruppia*, and freshwater SAV - coupled with the eutrophication model of Chesapeake Bay (CBEMP). The SAV biomasses depend on light temperature, light availability and nutrient concentrations generated by the CBEMP. The model successfully computed the spatial distribution and abundance of SAV for the period 1985-1994, and demonstrated that SAV distribution was primarily determined by computed light attenuation. Sensitivity analysis to reductions in nutrient and TSS loads indicated that nutrient controls will enhance abundance primarily in areas that presently support SAV. The dynamic SAV model originally developed by Cerco and Moore 2001 has been adapted and applied for modeling SAV biomass in other systems (e.g., Vaudrey et al. 2020, in progress, see Section 5.2.2) and has been updated for continued use and evaluation of SAV restoration by the CBEMP.

Kalra et al. 2020 two-way coupled a dynamic SAV biomass growth model within the open-sourced COAWST model framework (Coupled Ocean–Atmosphere–Wave–Sediment Transport) to evaluate idealized conditions and then eutrophication in a harbor for West Falmouth Harbor, Massachusetts (Table 5-4). The COAWST framework includes ROMS for 3D hydrodynamics, coupled with the water-column biogeochemistry model (BGCM) developed by Fennel et al. 2006. The coupling of the of the SAV growth model leads to the biological evolution of SAV properties based on temperature, light, and nutrient availability. The modeled SAV community exchanges nutrients, detritus, dissolved oxygen, and dissolved inorganic carbon with the water-column BGCM. Changes in SAV biomass and canopy characteristics also impact hydrodynamics, wave dynamics, and sedimentary dynamics (resuspension–transport). This model is truly 2-way coupled among hydrodynamics and water quality, biogeochemistry and nutrient cycling, and the SAV (Figure 5-11).

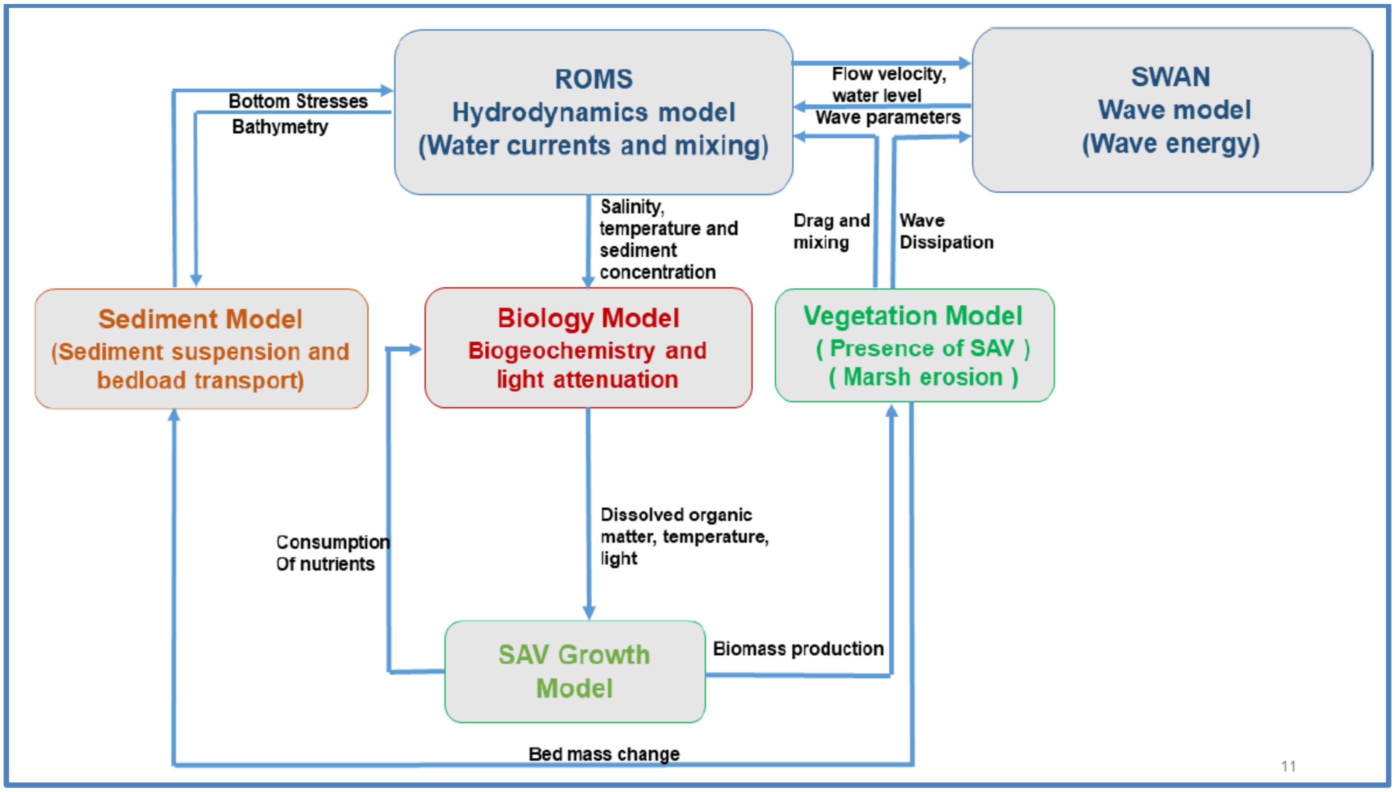

Figure 5-11 From Kalra et al. 2020 showing coupling of the SAV growth module implementation within the COAWST model.

An individual-based growth model for sugar kelp (Figure 5-12) was developed and coupled with SINMOD (Broch and Slagstad 2012, Broch et al. 2013, 2019, Figure 5-13) for Norway. The kelp growth model has been used to determine the best sites for kelp farms. The state variables in the kelp growth model are frond area (cm^{-2}), and internal nitrogen and carbon reserves (g N * g structural mass^{-1}). Environmental variables that affect kelp growth are water temperature, salinity, light intensity (PAR), nutrient concentrations (NO_2, NO_4), water current speed and latitude (implicitly through day length) (Broch and Slagstad 2012, Broch et al. 2019).

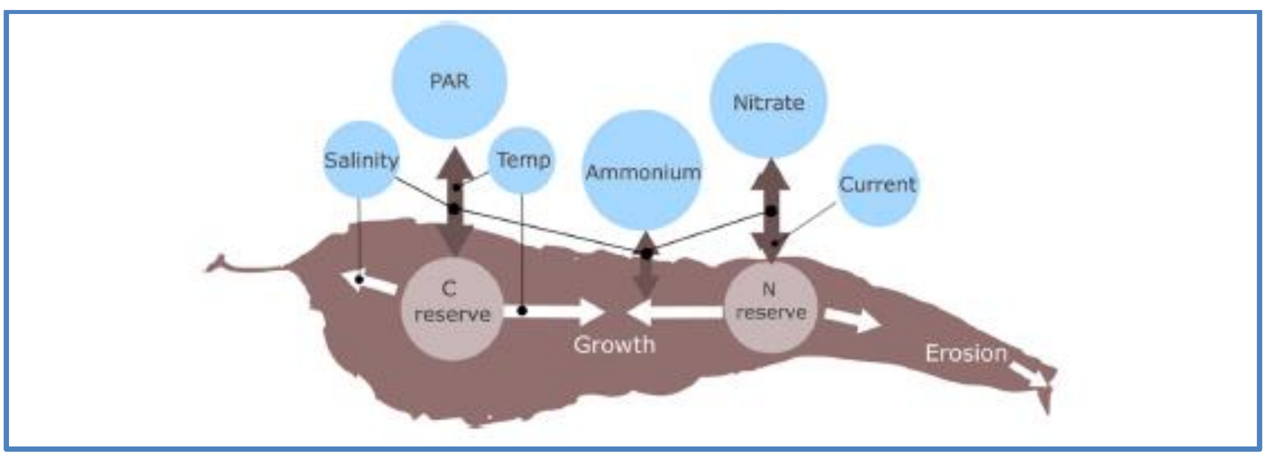

Figure 5-12 from Broch et al. 2019 describing how individual-based kelp growth is coupled within SINMOD.

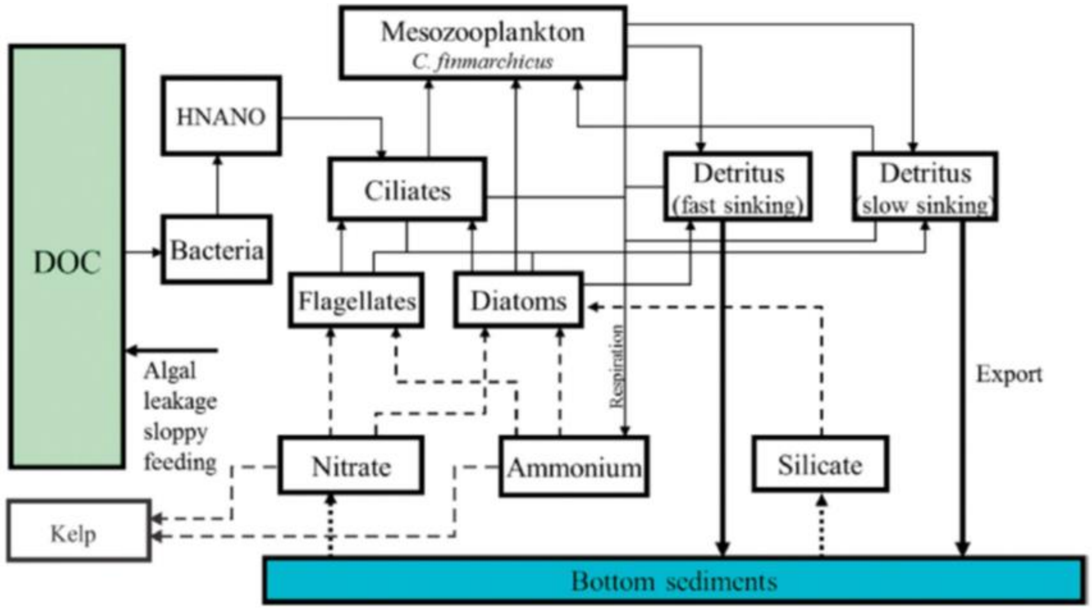

Figure 5-13 The SINMOD ecosystem model structure, adapted from Wassmann et al. (2006). HNANO: heterotrophic nanoflagellates (from Broch et al. 2013)

Similar to the coupled approach described above by Broch and Slagstad (2012), there is a dynamic seaweed module in the FV-COM hydrodynamic and eutrophication model framework being developed on the northwest coast of the U.S. (Wang et al. 2022). There is also a Seaweed AquaModel that appears to be under development and that is available online (http://www.aquamodel.net/Seaweed.html) that uses a biogeochemical approach with 3D hydrodynamic modeling to assist famers, regulators, and managers with placement and dimensions for seaweed farming in the U.S. The seaweed biomass is coupled within the biogeochemical modeling framework and is similarly affected by environmental conditions much like the FARM approach (e.g., Rose et al. 2014, Ferreira et al. 2007), and then uses seaweed assimilation and growth processes from Broch and Slagstad 2012, with data and parameters from C. Yarish.

Dynamic growth or population biomass models have the advantage of being one-way coupled with the hydrodynamics and two-way coupled with the eutrophication or biogeochemical models so that predicted effects on the living resource dynamics and the feedback on the ecosystem and nutrient cycling can be evaluated over time and under different scenarios. These coupled approaches can be applied at the system-scale or at the local or embayment-scale in LIS. There is overlap between the biogeochemical modeling that include living resources, and the dynamic biomass or growth modeling of living resources in this section. The modeled rates and processes for nutrient assimilation (SAV and seaweeds) or phytoplankton filtration (shellfish) are relatively similar for determining gains in growth or biomass. There is also a common set of environmental conditions or driving variables that affect plant growth and/or shellfish growth.

Table 5-6 lists Living Resource model classifications with some example models that could be used or adapted for evaluating DEP objectives and tasks.

Table 5-6 Living Resource Models

	Habitat Suitability Index Species Occurrence Health Index	Nutrient Cycling/ Biogeochemical with Living Resource	Dynamic Growth Population Biomass
Example Models	Silva et al. 2011; Vaudrey et al. 2013; Bricker et al. 2016; Sarker et al. 2021	Buzzelli et al. 1998; Bricker et al. 2015, 2018; Miller and Wands 2009; Brush and Nixon 2010	Filgueira et al. 2014, 2015; Cerco and Noel 2005, 2007; Bricker et al. 2015, 2018 Broch and Slagstad 2012
Independent Variables:			
Water level/depth	✓		
Temperature	✓	✓	✓
Light availability/TSS	✓	✓	✓
Salinity	✓	✓	✓
N, P, Si, Org-C		✓	✓
Chl-a	✓	✓	✓
Substrate/Bottom type	✓		✓
Time step	Month to Year	Hourly to daily	Daily to monthly
Coupling with Hydro-WQ	1-way	2-way	1-way and 2-way
Mass balance assumption	No	Yes (via nutrient cycling)	Yes (via individual to population biomass growth)
Model Outputs	Suitability or indicator score from 0.0 - 1.0	N or C in equivalent concentration units to HWQMS	Size in length or weight, growth (ΔS/Δt), abundance, size structure, biomass
Spatial Scaling	Applied for spatial cells or areas for embayment-scale or system-wide evaluation	Nutrient cycling at resolution of WQ cells or compartments to embayment-scale	Applied at species-level and locally (e.g., for reefs, culture sites, SAV beds)
Predicted outcomes to evaluate Hydro-WQ future scenarios	Changes in suitability or health scores based on seasonal or annual conditions	Changes in daily N, C concentrations evaluated at monthly to seasonal scale	Changes in daily size or growth evaluated as seasonal or annual growth rates; Changes in daily population abundance or biomass, evaluate change in seasonal or annual size structure or total biomass
Predicted outcomes to evaluate bio-extraction	N/A	N, C sources and sinks of LR in equivalent units to HWQMS	Daily N, P, Si uptake or filtration of Chl-a are assimilated by LR and removed from system; nutrient forms returned to system via excretion, egestion, and mortality

5.3 Section 5 References

ASMFC Habitat Committee. 1997. Guidance for the Development of the ASMFC Fishery Management Plan Habitat Sections and Source Documents. ASMFC Habitat Management Series #4. Atlantic States Marine Fisheries Commission, Washington DC. 15 p.

Arhonditsis, G.B. and M. T. Brett (2004) Evaluation of the current state of mechanistic. Aquatic Biogeochemical Modeling Vol. 271: 13–26

Barrett, L. T., S. J. Theuerkauf, J. M. Rose, H. K. Alleway, S. B. Bricker, M. Parker, D. R. Petrolia, R, C. Jones. 2022. Sustainable growth of non-fed aquaculture can generate valuable ecosystem benefits. Ecosystem Services 53, 101396

Batiuk, R.A., P. Bergstrom, M. Kemp, E. Koch, L. Murray, J.C. Stevenson, R. Bartleson, V. Carter, N. Rybicki, J. Landwehr, C. Gallegos, L. Karrh, M. Naylor, D. Wilcox, K. Moore, S. Ailstock, and M. Teichberg. 2000. Chesapeake Bay submerged aquatic vegetation water quality and habitat-based requirements and restoration targets: a second technical synthesis, 205. Annapolis: United States Environmental Protection Agency

Bradley, M. and S. Paton. 2018. Tier 1 2017 Mapping of *Zostera marina* in Long Island Sound and Change Analysis. 18 pp.

Bricker, S.B., J. Ferreira, C. Zhu, J. Rose, E. Galimany, G. Wikfors, C. Saurel, R. Landeck Miller, J. Wands, P. Trowbridge, R. Grizzle, K. Wellman, R. Rheault, J. Steinberg, A. Jacob, E. Davenport, S. Ayvazian, M. Chintala, and M. Tedesco. 2015. An Ecosystem Services Assessment using bioextraction technologies for removal of nitrogen and other substances in Long Island Sound and the Great Bay/Piscataqua Region Estuaries. NCCOS Coastal Ocean Program Decision Analysis Series No. 194. National Oceanic and Atmospheric Administration, National Centers for Coastal Ocean Science, Silver Spring, MD and United States Environmental Protection Agency, Office of Research and Development, Atlantic Ecology Division, Narragansett, RI. 154 pp + 3 appendices.

Bricker SB, Getchis TL, Chadwick CB, Rose CM, and Rose JM 2016 Integration of ecosystem-based models into an existing interactive web-based tool for improved aquaculture decision making. Aquaculture 453: 135–146.

Bricker SB, Ferreira JG, Zhu C, Rose JM, Galimany E, Wikfors GH, Saurel C, Miller RL, Wands J, Trowbridge P, Grizzle RE, Wellman K, Rheault R, Steinberg J, Jacob AP, Davenport ED, Ayvazian S, Chintala M, and Tedesco MA 2018 The role of shellfish aquaculture in reduction of eutrophication in an urban estuary. Environmental Science & Technology 52 (1): 173–183. [PubMed: 28994282]

Bricker, SB, Grizzle RE, Trowbridge P, Rose JM, Ferreira JG, Wellman K, Zhu C, Galimany E, Wikfors GH, and 10 other authors. 2020. Bioextractive removal of nitrogen by oysters in Great Bay Piscataqua River Estuary, New Hampshire, USA. Estuaries and Coasts 2020 Jan 1; 43: 23-38. Doi:10.1007/s12237-019-00661-8.

Brinton, A. J. 2021. Marsh restoration: Ribbed mussels (*Geukensia demissa*) as a revival mechanism to rebuild the coastal salt marshes of Long Island, New York. Posted August 2, 2021. https://doi.org/10.21203/rs.3.rs-359936/v1

Broch, O.J., Slagstad, D. (2012) Modelling seasonal growth and composition of the kelp *Saccharina latissima*. *Jour. Appl. Phycol.* **24**, 759–776

Broch OJ, Ellingsen IH, Forbord S, Wang X and others (2013) Modelling the cultivation and bioremediation potential of the kelp *Saccharina latissima* in close proximity to an exposed salmon farm in Norway. Aquacult. Environ. Interact. 4:187-206. https://doi.org/10.3354/aei00080

Broch OJ, Alver MO, Bekkby T, Gundersen H, Forbord S, Handå A, Skjermo J and Hancke K (2019) The Kelp Cultivation Potential in Coastal and Offshore Regions of Norway. Front. Mar. Sci. 5:529. doi: 10.3389/fmars.2018.00529

Brush MJ, Nixon SW. 2010. Modeling the role of macroalgae in a shallow sub-estuary of Narragansett Bay, RI (USA). Ecological Modelling 221: 1065-1079.

Buzzelli, C. P., R. L. Wetzel, M. B. Meyers. 1998. Dynamic Simulation of Littoral Zone Habitats in Lower Chesapeake Bay. II. Seagrass Habitat Primary Production and Water Quality Relationships. Estuaries, Vol. 21, No. 4, Part B (Dec., 1998), pp. 673-689

Cerco, C. and K. Moore, 2001. System-wide submerged aquatic vegetation model for Chesapeake Bay. Estuaries 24 (4), 522–534.

Cerco CF, and Noel MR. 2005. Evaluating ecosystem effects of oyster restoration in Chesapeake Bay. A report to the Maryland Department of Natural Resources. September 2005. US Army Engineer Research and Development Center, Vicksburg, MS.

Cerco, C. and M. R. Noel, 2007. Can oyster restoration reverse cultural eutrophication in Chesapeake Bay? Estuaries and Coasts 30 (2), 331–343.

Cerco, C. and M. R. Noel, 2010. Monitoring, modeling, and management impacts of bivalve filter feeders in the oligohaline and tidal fresh regions of the Chesapeake Bay system, Ecological Modelling 221 (2010) 1054–1064

Chen, H. 2019. Bayesian inference of environmental effects on seaweed production in Japan via a production-environmental suitability model. Botanical Studies 60:2. doi.org/10.1186/s40529-018-0250-x

Coen, L.D., R.D. Brumbaugh, D. Bushek, R. Grizzle, M.W. Luckenbach, M.H. Posey, S.P. Powers & S.G. Tolley. 2007. AS WE SEE IT. Ecosystem Services related to oyster restoration. *Marine Ecology Progress Series.* 341:303-307.

Dame, R.F., R.G. Zingmark & E. Haskin. 1984. Oyster reefs as processors of estuarine materials. *Journal of Experimental Marine Biology and Ecology*. 83(3):239-247.

DENNISON, W. C., R. J. ORTH, K. A. MOORE, J. C. STEVENSON, V. CARTER, S. KOLLAR, P. BERGSTROM, AND R. BATIUK. 1993. Assessing water quality with submersed aquatic vegetation. Habitat requirements as barometers of Chesapeake Bay health. *Bioscience* 43:86–94.

Di Toro, D.M., D.J. O'Connor and R.V. Thomann (1971) A dynamic model of the phytoplankton population in the Sacramento-San Joaquin Delta. In: *Nonequilibrium systems in natural water chemistry, advances in chemistry series 106*, ed. J.D. Hess, 131-180, Washington: American Chemical Society.

Dreyer, G.D. & W.A. Niering. 1995. Bulletin No. 34: Tidal marshes of Long Island Sound: Ecology, History and Restoration. Bulletins. Paper 34. 44pp.

Fasham, M. J. R., Ducklow, H. W. and McKelvie, S. M. (1990) A nitrogen-based model of plankton dynamics in the oceanic mixed layer, J. Mar. Res., 48(3), 591–639, doi:10.1357/002224090784984678.

Fennel, K., Wilkin, J., Levin, J., Moisan, J., O'Reilly, J., and D. Haidvogel. (2006). Nitrogen cycling in the Middle Atlantic Bight: results from a three-dimensional model and implications for the North Atlantic nitrogen budget. Global Biogeochemical Cycles, 20:GB3007.

Ferreira, J.G. .1995. ECOWIN — an object-oriented ecological model for aquatic ecosystems, Ecological Modelling, Volume 79, Issues 1–3, 1995, Pages 21-34, ISSN 0304-3800, https://doi.org/10.1016/0304-3800(94)00033-E

Ferreira, J.G., Hawkins, A.J.S., Bricker, S.B., 2007. Farm-scale assessment of shellfish aquaculture in coastal systems—the farm aquaculture resource management (FARM) model. Aquaculture 264, 160–174.

Ferreira JG, Sequeira A, Hawkins AJS, Newton A, Nickell TD, Pastres R, Forte J, Bodoy A, Bricker SB, (2009) Analysis of coastal and offshore aquaculture: Application of the FARM model to multiple systems and shellfish species. Aquaculture 292:129–138.

Ferreira JG, Hawkins AJS, and Bricker SB 2011 Chapter 1: The role of shellfish farms in provision of ecosystem goods and services In Shellfish Aquaculture and the Environment, ed. Shumway S, 1–31. Hoboken: Wiley - Blackwell.

Filgueira, R., Grant, J., Stuart, R., Brown, M.S., 2013. Ecosystem modelling for ecosystem-based management at bivalve aquaculture sites in data-poor environments. Aquacult. Environ. Interact. 4, 117–133.

Filgueira R, Guyondet T, Comeau LA, Grant J. 2014. A fully-spatial ecosystem-DEB model of oyster (Crassostrea virginica) carrying capacity in the Richibucto Estuary, Eastern Canada. Journal of Marine Systems 136(2014) 42-54.

Filguiera R, Guyondet T, Bacher C, Comeau LA. 2015. Informing marine spatial planning (MSP) with numerical modelling: A case-study on shellfish aquaculture in Malpeque Bay (Eastern Canada). Marine Pollution Bulletin http://dx.doi.org/10.1016/j.marpolbul.2015.08.048

Franks, P. (2002) NPZ Models of Plankton Dynamics: Their construction and coupling with physics, and application, J. 581 Oceanogr., 58 (2): 379–387.

Grabowski, J. H. & C. H. Peterson. 2007. Restoring oyster reefs to recover ecosystem services. Pp. 281–298 in: *Ecosystem engineers: plants to protists*, Cuddington, K., J. E. Byers, W. G. Wilson & A. Hastings, editors, Elsevier, Burlington, Massachusetts.

Holbach A, Maar M, Timmermann K, and Taylor D. 2020. A spatial model for nutrient mitigation potential of blue mussel farms in the wester Baltic Sea. Science of the Total Environment 736 (2020) 139624.

Inglis, G.J., Hayden, B.J., Ross, A.H. (2000) An Overview of Factors Affecting the Carrying Capacity of Coastal Embayments for Mussel Culture. NIWA, Christchurch. Client Report CHC00/69 (vi + 31 pp.).

Ismail, K. and Al-Shehhi, M. R.: Reviews and Syntheses (2022) Assessment of Biogeochemical Models in the Marine Environment, Biogeosciences Discuss. [preprint], https://doi.org/10.5194/bg-2021-351

Kalra, T. S., Ganju, N. K., and Testa, J. M. (2020) Development of a submerged aquatic vegetation growth model in the Coupled Ocean–Atmosphere–Wave–Sediment Transport (COAWST v3.4) model, Geosci. Model Dev., 13, 5211–5228, https://doi.org/10.5194/gmd-13-5211-2020

Kemp, W. M., Batiuk, R., Bartleson, R., Bergstrom, P., Carter, V., Gallegos, C. L., & ... Wilcox, D. J. (2004). Habitat Requirements for Submerged Aquatic Vegetation in Chesapeake Bay: Water Quality, Light Regime, and Physical-Chemical Factors. *Estuaries*, (3). 363.

Kim, J. K., Kraemer, G. P. & Yarish, C. 2014. Field scale evaluation of seaweed aquaculture as a nutrient bioextraction strategy in Long Island Sound and the Bronx River Estuary. Aquaculture 433:148-156.

Kim, J. K., Kraemer, G. P. & Yarish, C. 2015. Use of sugar kelp aquaculture in Long Island Sound and the Bronx River Estuary for nutrient extraction. Mar. Ecol. Prog. Ser. 531:155-166.

Koch, E.W. and S. Beer. 1996. Tides, light and the distribution of *Zostera marina* in Long Island Sound, USA. *Aquatic Botany* 53:97–107.

Koch, E.W. et al. 2001. Beyond light: physical, geological, and geochemical parameters as possible submersed aquatic vegetation habitat requirements. Estuaries, 24(1), pp.1-17.

Kim, J.K., Michael Stekoll & Charles Yarish (2019) Opportunities, challenges and future directions of open-water seaweed aquaculture in the United States, Phycologia, 58:5, 446-461, DOI: 10.1080/00318884.2019.1625611

Kim J.K., C. Yarish, E.K. Hwang, M.S. Park and Y.D. Kim. 2017. Seaweed aquaculture: cultivation technologies, challenges and its ecosystem services. *Algae* 32(1): 1-13 (doi.org/10.4490/algae.2017.32.3.3).

Kim J.K., G.P. Kraemer and C. Yarish. 2015. Sugar Kelp Aquaculture in Long Island Sound and the Bronx River Estuary for Nutrient Bioextraction and Ecosystem Services. *Marine Ecology Progress Series* 531:155-166, DOI: 10.3354/meps11331.

Laney, R.W. 1997. The relationship of seagrass ecological value to species managed by the ASMFC: A summary for the ASMFC Submerged Aquatic Vegetation Subcommittee in Stephan, C.D. and T.E. Bigford, Editors, Atlantic Coastal Submerged Aquatic Vegetation: a review of its ecological role, anthropogenic impacts, state regulation and value to Atlantic coastal fisheries. ASMFC Habitat Management Series No. 1. Washington, DC

Langton, R., Simona Augyte, Nichole Price, John Forster, Thomas Noji, Gretchen Grebe, Adam St. Gelais, and Carrie J. Byron. 2019. An Ecosystem Approach to the Culture of Seaweed. NOAA Tech. Memo. NMFS-F/SPO-195, 24 p.

Lavaud R, La Peyre MK, Casas SM, Bacher C, La Peyre JF. 2017. Integrating the effects of salinity on the physiology of the eastern oyster, *Crassostrea virginica*, in the northern Gulf of Mexico through a Dynamic Energy Budget model. Ecological Modelling, 363: 221-233.

Lavaud R, La Peyre MK, Justic D, La Peyre JF. 2021. Dynamic Energy Budget modelling to predict eastern oyster growth, reproduction, and mortality under river management and climate change scenarios. Estuarine Coastal and Shelf Science, 251, 107188, https://doi.org/10.1016/j.ecss.2021.107188.

LISS (Long Island Sound Study). 2003. Long Island Sound Habitat Restoration Initiative, Technical Support for Coastal Habitat Restoration. Section 3: Submerged Aquatic Vegetation. EPA Long Island Sound Office, Stamford CT.

LISS (Long Island Sound Study). 2018. Long Island Sound Habitat Restoration Initiative, Technical Support for Coastal Habitat Restoration. Section 7: Natural Shellfish Beds (Version 1.0, August 2018).

Miller, R. E. L. and J. R. Wands. 2009. Applying the System Wide Eutrophication Model (SWEM) for a preliminary quantitative evaluation of biomass harvesting as a nutrient control strategy for Long Island Sound. HydroQual, Inc. 50 p.

NYSDEC (2017) Eelgrass and Water Quality: A Prospective Indicator for Long Island Nitrogen Pollution Management Planning. Tech. report by Liana Simpson and Soren Dahl, New York State Department of Environmental Conservation, Division of Marine Resources, LINAP Newsletter, October. https://content.govdelivery.com/accounts/NYSDEC/bulletins/1bf6e4b (note: document is referenced in this link but is not available for download)

NYS STF (New York State Seagrass Task Force). 2009. Final Report: Recommendations to the New York State Governor and Legislature. http://www.dec.ny.gov/docs/fish_marine_pdf/finalseagrassreport.pdf

Parker M, and Bricker S. 2020. Sustainable oyster aquaculture, water quality improvement, and ecosystem service value potential in Maryland Chesapeake Bay. Journal of Shellfish Research 39(2): 269-281.

Powell EN, Hofmann EE, Klinck JM, Ray SM (1992) Modeling oyster populations. A commentary on filtration rate. Is faster always better? J Shellfish Res 11:387-398

Riisgård, H.U. 2001. On measurement of filtration rates in bivalves-the stony road to reliable data: review and interpretation. *Marine Ecology Progress Series*. 211:275-291.

Roleda, M. W. and C. L. Hurd (2019) Seaweed nutrient physiology: application of concepts to aquaculture and bioremediation, Phycologia, 58:5, 552-562, DOI: 10.1080/00318884.2019.1622920

Rose JM, Bricker SB, Tedesco MA, Wikfors GH (2014) A role for shellfish aquaculture in coastal nitrogen management. Environ Sci Technol 48:2519–2525. doi:10.1021/es4041336

Rose JM, Bricker SB, and Ferreira JG. 2015a. Modeling shellfish farms to predict harvest-based nitrogen removal. Marine Pollution Bulletin 453: 135–146.

Rose, J.M., S.B. Bricker, S. Deonarine, J.G. Ferreira, T. Getchis, J. Grant, J.K. Kim, J.S. Krumholz, G.P. Kraemer, K. Stephenson, and G.H. Wikfors. 2015b. Nutrient bioextraction. Encyclopedia of sustainability science and technology, 10, 2015.

Riley, G.A., H. Stommel, and D.F. Bumpus (1949) Quantitative ecology of the plankton of the Western North Atlantic. *Bulletin of the Bingham Oceanographic Collection* 12: 1-169.

Sarker, S., M. Akter, M. S. Rahman, M. M. Islam, O. Hasan, M. A. Kabir, M. M. Rhaman (2021) Spatial prediction of seaweed habitat for mariculture in the coastal area of Bangladesh using a generalized additive model. Algal Research, December 2021. doi.org/10.1016/j.algal.2021.102490

Shumway, S.E. 1996. Natural environmental factors. Pp. 467-513 in: The Eastern Oyster *Crassostrea virginica*, V.S. Kennedy, R.I.E. Newell & A.F. Eble, editors. Maryland Sea Grant College, University of Maryland, College Park, Maryland. 772 pp.

Steele, J.H. (1974) *The structure of marine ecosystems*. Cambridge: Harvard University Press.

Stewart Van Patten, M. and C. Yarish. "Bulletin No. 39: Seaweeds of Long Island Sound" (2009). Bulletins. Paper 40. http://digitalcommons.conncoll.edu/arbbulletins/40

Sverdrup, H. (1953) On Conditions for the Vernal Blooming of Phytoplankton. ICES Journal of Marine Science, 18, 287-295. https://doi.org/10.1093/icesjms/18.3.287

Thayer, G.W., Kenworthy, W.J. and Fonseca, M.S., 1984. *Ecology of Eelgrass Meadows of the Atlantic Coast: a community profile* (No. FWS/OBS-84/02). National Marine Fisheries Service, Beaufort, NC (USA). Beaufort Lab.; Virginia Univ., Charlottesville (USA). Dept. of Environmental Sciences.

Theuerkauf SJ, Barrett LT, Alleway HK, Costa-Pierce BA, St. Gelais A, Jones RC (2021) Habitat value of bivalve shellfish and seaweed aquaculture for fish and invertebrates: pathways, synthesis and next steps. Reviews in Aquaculture, DOI: 10.1111/raq.12584.

USFWS. 1981. Standards for the development of habitat suitability index models. Washington, DC: Division of Ecological Services, U.S. Fish and Wildlife Service, Department of the Interior. 103 pp.

Vaudrey, Jamie M. P. 2008. Establishing Restoration Objectives for Eelgrass in Long Island Sound, Part 1: Review of the Seagrass Literature Relevant to Long Island Sound. *Department of Marine Sciences, University of Connecticut.*

Vaudrey, J.M.P., J. Eddings, C. Pickerell, L. Brousseau., C. Yarish. 2013. Development and application of a GIS-based Long Island Sound Eelgrass Habitat Suitability Index Model. Final report submitted to the New England Interstate Water Pollution Control Commission and the Long Island Sound Study. 171 p. + appendices.

Vaudrey, J.M.P., Krumholz, J., Calabretta, C. (2019) Eelgrass success in Niantic River Estuary, CT: quantifying factors influencing interannual variability of eelgrass (*Zostera marina*) using a 30-year dataset. University of Connecticut, Department of Marine Sciences, Groton, CT. Final report prepared for the Niantic Nitrogen Work Group. 200 p.

Vaudrey, J.M.P., Krumholz, J., Calabretta, C. (2020) DRAFT Model Report, v. 2020-11-11. University of Connecticut, Department of Marine Sciences, Groton, CT. prepared for the Niantic Nitrogen Work Group. 114 p.

Van Patten, M. A. (2015) "Seaweeds Clean Long Island Sound", Wrack Lines. 96. https://opencommons.uconn.edu/wracklines/96

Walsh, J.J. and R. A. Dugdale (1971) A simulation model of the nitrogen flow in the Peruvian upwelling system. *Invest. Pesq*. 35, 309-330.

Walsh, J.J., D.A. Dieterle and M.B. Meyers (1988) A simulation analysis of the fate of phytoplankton within the mid-Atlantic Bight. Cont. Shelf Res. Volume 8, Issues 5–7, Pages 757-787, ISSN 0278-4343, https://doi.org/10.1016/0278-4343(88)90076-3.

Wang T, Yang Z, Davis JP, Edmundson SJ. 2022. Quantifying nitrogen bioextraction by seaweed farms – a real-time modeling-monitoring case study in Hood Canal, WA. Pacific Northwest National Laboratory, operated by Battelle for the United States Department of Energy, Contract # DE-AC05-76RL01830.

Wroblewski, J. S., Sarmiento, J. L. and Flierl, G. R. (1988) An Ocean Basin Scale Model of plankton dynamics in the North Atlantic: 1. Solutions For the climatological oceanographic conditions in May, Global Biogeochem. Cycles, 2(3), 744 199–218, doi:10.1029/GB002i003p00199.

Xiao X, Agusti S, Lin F, Li K, Pan Y, Yu Y, Zheng Y, Wu J, Duarte CM. 2017. Nutrient removal from Chinese coastal water by large-scale seaweed aquaculture. Scientific Reports 7, Article number: 46613 (2017)

Zhang J, Kitazawaa D, Yang C. 2015. A numerical modeling approach to support decision-making on design of integrated multitrophic aquaculture for efficiently mitigating aquatic waste. Mitigation and Adaptation Strategies for Global Change, April 2015. DOI: 10.10087/s11027-015-9652-1

6. TAC Recommendations for DEP Scope of Work Tasks for Living Resources

DEP's Scope of Work Tasks are restated in the form of actionable items for the TACs consideration in Table 6-1.

Table 6-1 DEP's Scope of Work Tasks

Tasks to be completed for living resources models and Integrated Model Framework (IMF)	
Task No.	Description
Task 1	Project Scoping includes Technical Advisory Committee for Living Resources to Inform and assist DEP to develop RFP requirements to achieve living resources objectives for project
Task 2	*Regional system-wide scale forecast model to link living resources with system-wide LIS-HWQMS (ROMS-RCA) under future condition scenarios (e.g., climate change)* Identify salient features of a system-wide living resource model to link with ROMS-RCA and identify example models. Which of the LR models can explicitly link valued ecosystem services such as SAV, tidal wetlands, macroalgae, and oyster (or other?). Note that results from the linked models will be used to facilitate resource management decisions that take into consideration climate change, sea level rise, etc.
Task 3	*Pilot testing at local embayment-tidal river scale to link living resources with existing embayment-tidal river hydrodynamic and water quality models; open boundary conditions to be extracted from system-wide LIS-HWQMS (ROMS-RCA)* Identify living resource model features and examples of models (giving priority to SAV) that are useful for embayment or tidal river scale modeling given (1) existing embayment or tidal river hydrodynamic and water quality models (ROMS-RCA or some other models, e.g., EFDC and WASP) and (2) open boundary conditions (e.g., extracted from ROMS-RCA), and (3) watershed loading.
Task 4	*Pilot testing of management questions for evaluation of bioextraction and "green" nitrogen removal strategies with living resource models using LIS-HWQMS (ROMS-RCA) generated nutrient conditions under existing and future scenarios.* Identify LR model/approaches that could be used to represent bioextraction strategies (e.g., oyster aquaculture) and "green" nitrogen removal strategies (e.g., sugar kelp farms) to be implemented using the living resource models identified in conjunction with Tasks 2 and 3. The goal in implementing the removal strategies is to quantify nutrient removal, potential effectiveness, and economic valuation of the technologies. Scenarios representing existing and future conditions will be analyzed.

6.1 TAC Assessment of Regional System-Wide Scale Forecast Models

Task 2 of DEP's LR scope of work calls for identifying or developing system-wide scale forecast model(s) to link living resources to changes in future conditions (e.g., nutrient management and climate change)

DEP objectives for linking Living Resource Models within the IMF are listed in Table 3-1 (see Task 2 – 4). Within Section 3 of this report, DEP further describes the project objectives needed from the coupled IMF numerical model as:

- Derive site-specific Numeric Nutrient Criteria (NNC) to achieve water clarity threshold targets for restoration of SAV in coastal embayments and tidal river/estuaries;
- Assess macroalgae (seaweed) and shellfish for bioextraction, aquaculture and "green" technologies as Best Management Practices (BMPs) for *in-situ* nutrient management strategies;
- Assess climate change impacts on Living Resources with linkage to the system-wide ROMS-RCA hydrodynamic – water quality model framework.

Our literature review and summary of the key living resources for LIS and their effects on water quality and bio-extractive properties (see Section 4 and Section 5), and the available models for the key LR in LIS and similar systems (see Section 5), support our recommended path forward for the development, testing, validation, and coupling of the living resource models within the IMF currently supported by DEP.

Within the system-wide domain, the living resources of interest -- SAV, shellfish and seaweed -- are found primarily in shallow waters of embayments, tidal rivers/estuaries, and the nearshore coastal waters of LI Sound. Seaweed farming of kelp in the shallow waters of Southern New England, for example, has been described for LI Sound (Van Patten, 2015) and Narragansett Bay (Brush and Nixon, 2010) and Suffolk County NY passed the "Kelp Bill" in December 2021 to allow shellfish leases in shallow areas of Peconic Bay and Gardiners Bay to be used for seaweed farming.

In contrast to shallow water operations, Kim et al. (2019) reviewed the past and current status of seaweed aquaculture in the United States including a discussion of the potential opportunities of seaweed aquaculture in offshore open-water areas. Within the Economic Exclusion Zone (EEZ), large areas of the continental shelf are available to produce large seaweed harvests without conflicts with recreational and/or fishing activity that are often encountered in shallow water operations. Permits can also be obtained for offshore operations with fewer obstacles than nearshore waters where there are current permitting restrictions for seaweed cultivation areas for human consumption.

Seaweed cultivation could be desirable, however, in open offshore waters or in shallow coastal areas that are not certified waters for shellfish harvesting. As described by Kim et al. (2019), potential markets for seaweed include food products and other uses such as biofuels, soil amendments, pharmaceuticals, etc. that might not raise the same health issues related to consumption of seaweed as a food product. From a water quality management perspective, the ability to evaluate seaweed cultivation in offshore and open waters with the system-wide IMF would allow for a fuller evaluation of the possible ecosystem services contributions of seaweed aquaculture to water quality improvements and other economic benefits of seaweed farming.

As discussed in Section 1, the system-wide ECOMSED-RCA model was used to support evaluations of the impact of living resources on *in-situ* nutrient removal in LI Sound for comparison to watershed-based nutrient reduction strategies. Bricker et al. (2015, 2018) used SWEM to link hydrodynamic and water quality output as input to EcoWin and FARM models that included shellfish growth to estimate in-situ removal of Chl-a and nutrients via shellfish production and harvest. Nutrient removal capabilities by shellfish culture have been evaluated with local-scale application of FARM models in several systems (Rose et al. 2015) and BMP assessments of oyster aquaculture benefits in Chesapeake Bay were evaluated using a 1-way standalone oyster model (Parker and Bricker, 2016).

Miller and Wands (2009) modified the RCA water quality model code to add new source and sink terms as forcing functions to quantify the impact of fixed biomass distributions of shellfish and seaweed on nutrient removal rates in the LI Sound region. Based on their preliminary analysis of nutrient removal rates and potential improvements in dissolved oxygen, Miller and Wands (2009) concluded that shellfish aquaculture and harvesting of seaweed/kelp could provide realistic *in-situ* approaches for nutrient management strategies.

Recommendation #1: The TAC recommends that DEP build on the earlier SWEM-based investigation (Miller and Wands, 2009) using the system-wide ROMS-RCA model currently under development for the LIS-HWQMS. Miller and Wands (2009) outlined next steps for incorporation of mechanistic mass balance-based sub-models to represent shellfish and seaweed as dynamic state variables in the RCA water quality model. The fixed biomass/forcing function approach used by Miller and Wands is likely appropriate to support an updated screening-level analysis of nutrient removal by shellfish and seaweed. As HDR is currently using the old SWEM ECOMSED-RCA source code for testing comparisons of Water Year 1995 simulations with the new implementation of ROMS-RCA, the old RCA source code and documentation of the methods used are available at HDR (Thuman, pers. comm., 2022). The old RCA code could be added to the current version of RCA to develop fixed-biomass (time invariant) forcing functions for shellfish and seaweed. The TAC recommends that the analysis performed by Miller and Wands be re-visited, as needed, to update this preliminary assessment of nitrogen fluxes accounted for by living resources with the improved system-wide ROMS-RCA model.

Recommendation #2: In addition to the RCA source code modification developed for the Miller and Wands analysis of oysters and seaweed, the RCA source code was also modified as part of SWEM and other projects to incorporate water quality impacts of bivalve filter feeders, SAV and benthic algae. Versions of the RCA model, for example, were applied to investigate the water quality impact of oysters in Jamaica Bay (HydroQual, 2002) and SAV and benthic algae in South Florida wetlands (HydroQual, 1995) (Thuman, 2022, personal communication).

The TAC recommends that DEP build on previous SWEM-based living resource modeling projects by taking advantage of the availability of different versions of RCA source code developed to support living resource assessments. Living resource models developed by HydroQual were based on SAV and oyster models developed by Cerco and Moore (2001) and Cerco and Noel (2007) for the Chesapeake Bay estuary Model. The TAC recommends that source code previously developed by HydroQual under the SWEM and other projects be identified from HDR archives, documented, reviewed and considered as living resource sub-model candidates for upgrading the LIS-HWQMS version of the RCA model.

The TAC recommends that DEP take advantage of previous HydroQual source code efforts to systematically upgrade the capability of the current LIS-HWQMS version of RCA to support living resource sub-models for SAV, bivalve filter feeders and seaweed (macroalgae). In addition to the living resource sub-models developed by HydroQual under SWEM and other projects, there are several examples of coupled living resource and biogeochemical models reported for LI Sound or similar systems referenced in Section 5 that can be used to support upgrading the LIS-HWQMS version of RCA. The open source code for shellfish and SAV models developed for the Chesapeake Bay Environmental Modeling Program (CBEMP), for example, could be obtained and used to support upgrading RCA for the LIS-HWQMS project.

In the interest of providing DEP with the capability to pursue a phased approach for living resource assessments, the TAC recommends that living resource sub-models be (a) internally coupled with the RCA water quality model to support living resources simulations based on both (b) fixed (time-invariant) and (c) dynamic (time-variable) predictive biomass models for SAV, seaweed and shellfish. Following the example of the CBEMP experience, living resource sub-models must be internally coupled with the RCA water quality model to demonstrate 2-way feedback between living resources, water quality and biogeochemical cycling. Finally, an option should be included in the upgrade of RCA code to either activate (On) or suppress/bypass (Off) simulation of living resource sub-models. This option will save runtime for system-wide applications of the upgraded ROMS-RCA model framework.

Recommendation #3: The TAC recommends that there are two best uses of the system-wide ROMS-RCA model framework as follows:

Best Use #1: The system-wide ROMS-RCA model can provide open water hydrodynamic and water quality boundary conditions as input to nested, fine-grid hydrodynamic and water quality models of embayments, tidal rivers/estuaries and nearshore coastal waters (see Task 3). As described in Section 3, this recommendation is consistent with EPA's "Nex-Gen" strategy to customize the application of Numeric Nutrient Criteria/Thresholds for similar spatially defined sub-group watersheds of the LI Sound drainage basin (USEPA, 2015). In addition to water quality evaluations, the system-wide ROMS-RCA hydrodynamic and water quality model can also provide open water boundary conditions for linkage with local-scale hydrodynamic and water quality models to support development of living resource models for local-scale embayments, tidal rivers/estuaries and nearshore coastal waters as described under Task 3 below.

Best Use #2: As discussed under Recommendation #2 above, the ROMS-RCA model framework can directly incorporate living resource sub-models for SAV, shellfish and seaweed in the IMF by upgrading the current version of RCA being developed for the LIS-HWQMS. Living resource evaluations can then be performed with the ROMS-RCA framework at the system-wide scale, if desired, to evaluate the responses of water quality and living resources to system-wide management scenarios. This recommendation would support, for example, ecosystem services assessments of seaweed farming operations in the deeper open waters of either LI Sound or the NY Bight for user-specified spatial domains of interest within the system-wide grid. The upgraded ROMS-RCA framework with living resource sub-models would also be available to support development of nested, finer-scale models of embayments, tidal rivers/estuaries or nearshore coastal waters as described below under Task 3 and Task 4.

At the system-wide scale, the spatial extent of the distribution of living resources is limited (see Figure 5-2 and Figure 5-5) compared to the much larger spatial domain of the LIS-HWQMS. As the living resources considered for the LIS-HWQMS are typically limited to shallow waters of embayments, tidal rivers/estuaries and nearshore coastal waters, the majority of the system-wide deep-water grid cells will be defined by zero biomass. Living resource biomass will only be simulated within the system-wide spatial grid resolution of embayments, tidal rivers/estuaries or nearshore waters that are of interest for a particular application. Living resources might be modeled, for example, for all the embayments of Connecticut without modeling living resources in the embayments of Long Island, NY Harbor or the NJ coast.

Although the system-wide resolution of shallow water areas most likely will not be adequate for a detailed assessment of the responses of living resources and water quality to management scenarios such as spatial gradients of water depth and light availability that impact SAV. The system-wide grid resolution may, however, be sufficient to support simplified, screening level assessments. The system-wide grid resolution of local embayments and tidal rivers/estuaries may also be appropriate to support empirical index models of living resources (e.g., Habitat Suitability Index, HSI) with linkage of ROMS hydrodynamic and RCA water quality results as input to a selected index model. Screening level assessments based on analyses of the relative differences of outputs between alternative scenarios provide the best metrics for evaluation of the relative merits of alternative management scenarios.

Recommendation #4: Two-way coupling with hydrodynamics and living resources (see Figure 2-5[D]) is not recommended for this project at the system-wide scale. Although it is well known that oyster reefs and SAV beds can influence local-scale velocity and sedimentation processes in shallow water, the distribution of these living resources is not likely to alter large-scale circulation or sedimentation processes within the system-wide model domain. In addition, conclusions drawn from the outcome of future conditions based on management scenarios for nutrients or climate change/sea level rise are not likely to be impacted by 2-way coupling of living resources and hydrodynamics at the system-wide scale.

Recommendation #5: The scope of work for Task 2 specifically addresses assessments of the impact of climate change on living resources through linkage with the system-wide ROMS-RCA hydrodynamic and water quality model as part of the IMF. Expected impacts of climate change that threaten estuarine and coastal waters such as LI Sound include Sea Level Rise (SLR), altered patterns of precipitation and river discharge and ocean acidification (Source: EPA Climate Change Adaptation Resource Center: https://www.epa.gov/arc-x/climate-adaptation-and-estuaries). Two decades ago, Najjar et al. (2000) assessed the potential impacts of climate change in the Mid-Atlantic coastal region. They reviewed available data and considered possible impacts to precipitation, streamflow, wetlands, salinity intrusion, water quality, plankton, SAV, and fish and shellfish.

SLR will inundate low elevation shorelines, displace wetlands and marshes, increase the tidal range in bays, estuaries and tidal rivers and increase periodic coastal inundation during the highest tides from normal full moon and new moon patterns (“King Tides”) and storm surge from extreme weather events. Projected increases for intensity of precipitation will lead to increased discharge from coastal rivers and urban stormwater, erosion and sedimentation, and increased watershed-driven nutrient loading that can impact coastal eutrophication processes. Changes in precipitation, coastal river discharge and SLR will impact salinity intrusion into low salinity areas that can, in turn, lead to degradation of water quality conditions such as saltwater contamination of water supply sources (e.g., water intakes in tidal-fresh Hudson River or coastal groundwater) and living resources such as desirable habitat conditions for living resources (e.g., range of salinity tolerance for oysters). The increasing rise of atmospheric carbon dioxide leads to acidification of coastal and open ocean waters which has been shown to alter the balance if minerals in seawater needed to sustain healthy populations of living resources such as shellfish.

Detailed assessments of the impacts of climate change on water quality conditions and living resources, such as numerical modeling evaluations, have been performed for several coastal and estuarine systems including Chesapeake Bay (Cerco and Tian, 2021; Hood et al., 2021). Such a level of detail, however, is clearly beyond the Scope of Work envisioned for the proposed DEP pilot study of living resources that will be based largely on existing data.

The TAC understands that whoever our “future selves” are who will be involved in future water quality and living resources assessments of climate change will thank DEP and the LI Sound Study for early consideration of screening-level assessments of climate change during model development, calibration and management scenario testing under the ongoing LIS-HWQMS project. If climate change impacts are not considered for LI Sound modeling until the IMF is completed there is the possibility that important insight about climate-induced changes in the living resources of LI Sound may be overlooked. The integration of living resource models with the ROMS-RCA hydrodynamic and water quality models can have utility for State, local and federal “decision-makers” not only at the present time but also in anticipation of LI Sound living resource responses to climate change in the decades to come (e.g., 2035, 2055, 2075, etc.).

The TAC recommends that relatively simple climate change analyses be incorporated into the ROMS-RCA framework as one of the management scenarios, and at least to some degree, can be linked into the living resource models that will be incorporated into the IMF. Screening-level approximations to the potential impact of climate change can be represented in the ROMS-RCA model framework by adjustments of input data to the ROMS hydrodynamic model.

Projections of Sea Level Rise can be simulated through simple adjustments to open-water boundary conditions for water level along the continental shelf of the NY Bight. Projected changes in Sea Level Rise for Connecticut, for example, are shown in Figure 6-1 (O'Donnell, 2019).

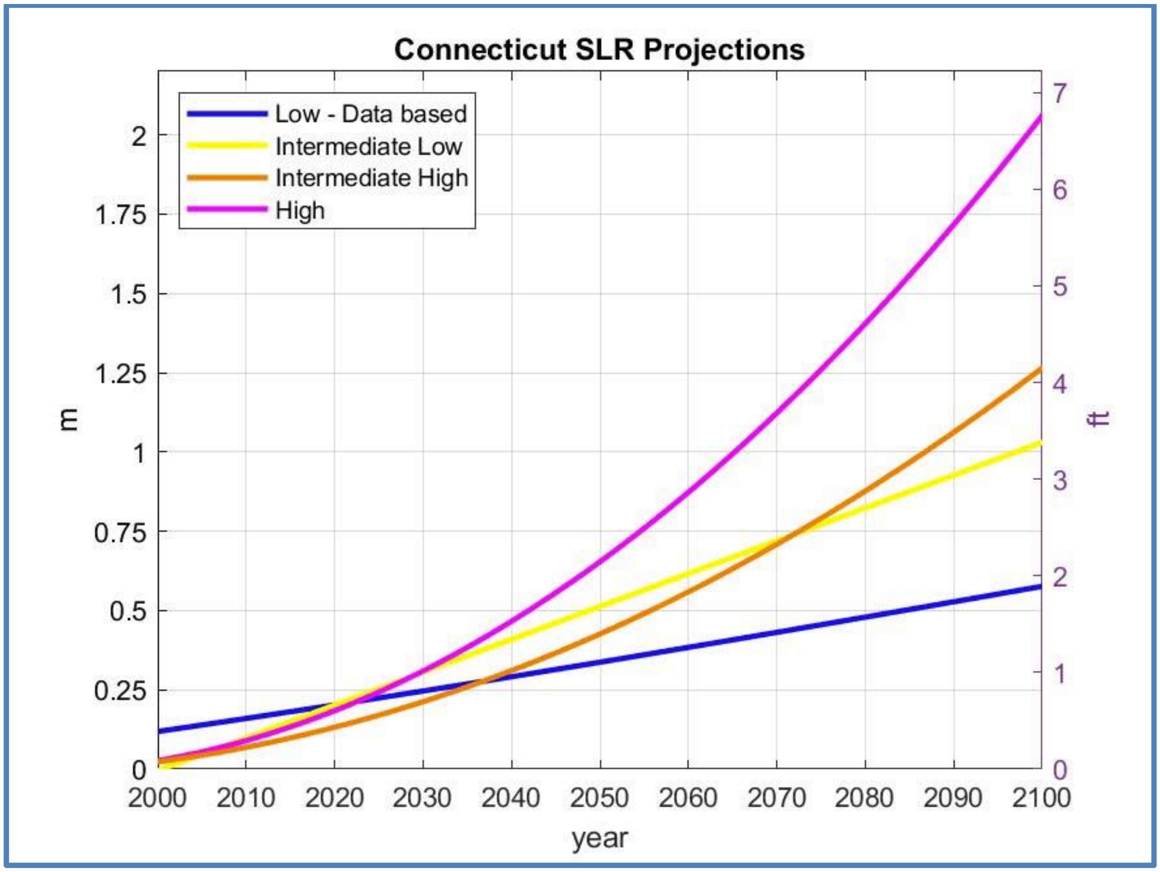

Figure 6-1 Sea level rise projections for Connecticut based on local tide gage observations (blue line) and IPCC (2013) RPC 4.5 model simulations near Long Island Sound (yellow line) Source: O'Donnell (2019)

Projections of watershed-based nonpoint source runoff from changes in precipitation intensity can be simulated without running watershed models with relatively simple percentage change adjustments to streamflow data compiled as input for calibration and validation of the ROMS-RCA model to represent seasonal variation in expected discharge conditions for coastal watersheds and perhaps stormwater runoff. Botero-Acosta et al. (2022) estimated climate induced changes in streamflow and water temperature by mid-century and end of century based on individual SWAT watershed models developed across the Atlantic Coast from Maine to Georgia. Projected seasonal changes in streamflow are shown in Figure 6-2 for watersheds from the north to south (Maine Bay to Satilla-Altamaha) for the mid-century projection (2040-2069). Winter streamflow (blue) for the Massachusetts Bay and Hudson watersheds is expected to increase ~ 20 to 40% while summer streamflow (orange) shows a decrease of ~ 10% to 0%.

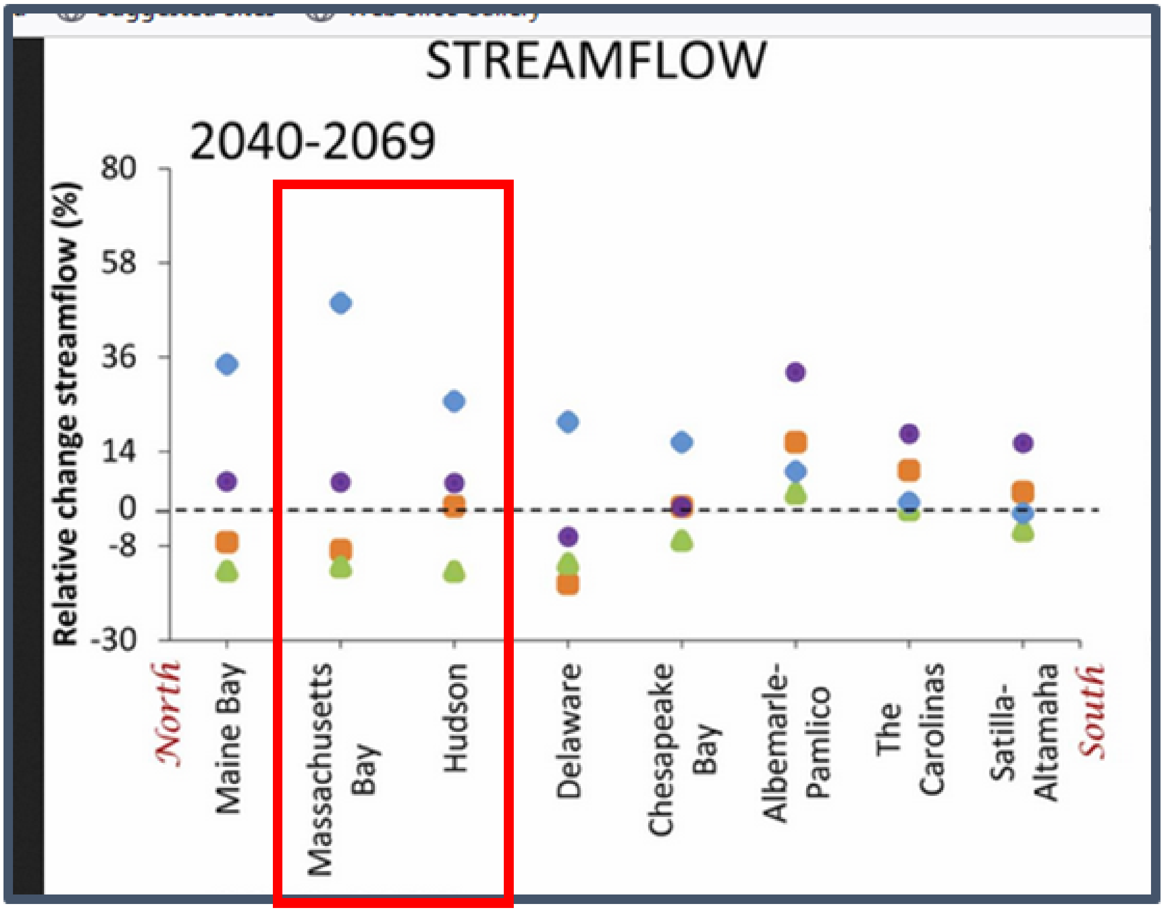

Figure 6-2 Watershed-mean seasonal changes in streamflow in watershed from north to south (Maine to Georgia) Source: Botero-Acosta et al. (2022)

Although changes in air temperature are anticipated from climate change, there are several atmospheric forcing functions that would need to be changed for hydrodynamic model input to properly account for expected changes in air temperature (e.g., relative humidity). This would require coordination with climate modelers to obtain simulated scenarios to completely specify projected meteorological and atmospheric forcing input files needed for the ROMS hydrodynamic model. A much simpler approach, however, for a screening level assessment of changes in water temperature was used by Testa et al. (2021) for an idealized assessment of future scenario evaluations of the potential impacts of climate change warming of water temperature. In this study, simple sensitivity tests for water temperature were modeled with small ΔT increments (+0.75 and + 1.25 ^{o}C) of water temperature in the Chester River in Chesapeake Bay.

Recommendation #6: Atmospheric deposition is incorporated in the system-wide LI Sound model as an external source term for nutrient loading. TAC member Lewis Linker noted that atmospheric deposition of N was a significant historical source of total N loading to the Chesapeake Bay watershed and that implementation of Clean Air Act emission controls has resulted in large decreases of atmospheric N loading over the past 20 years. Despite the reduction from the Clean Air Act, atmospheric N loading still accounts for about 25% of total annual loading of N to the Chesapeake Bay watershed. Burns et al.

(2021) compiled historical atmospheric deposition data with modeled projections to document 100 years of atmospheric N loading from 1950 – 2050 (Figure 6-3).

The TAC recommends that EPA and DEP consider taking advantage of the regional Community Multi-Scale Air Quality (CMAQ) model. CMAQ offers an excellent up-to-date data source for atmospheric deposition loading of N that can provide spatial and time-dependent data as input to the LI Sound system-wide model (https://www.epa.gov/cmaq).

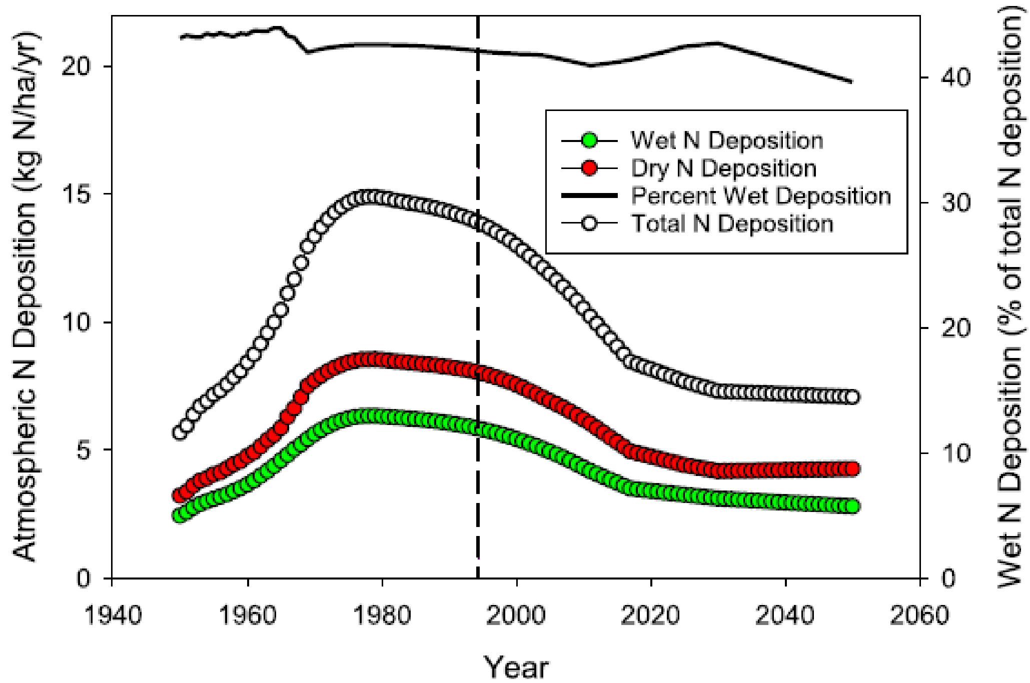

Fig. 3. Annual atmospheric N deposition estimates for the Chesapeake Bay watershed during 1950–2050. Total N deposition, wet and dry N deposition, and percent wet N deposition relative to total N deposition are depicted. Dashed vertical line indicates the year 1995.

Figure 6-3 Annual atmospheric N deposition estimates for the Chesapeake Bay watershed during 1950 – 2050. Source: Burns et al. (2021)

<u>Recommendation #7</u> The TAC recommends that EPA and DEP reach out to the Peconic Estuary Program (https://www.peconicestuary.org/) to let them know about the ongoing LIS-HWQMS study. The open water boundary for the Peconic Estuary TMDL model (Tetra Tech, 1999) is in Block Island Sound which is included in the system-wide ROMS-RCA model domain. The Peconic Estuary Program may be interested in either model calibration/validation results and/or management scenarios for nutrients and climate change/sea level rise for use in their own modeling studies of the Peconic Estuary system such as updating the Peconic Bay TMDL (PEP, 2007) (https://www.peconicestuary.org/total-maximum-daily-load-for-nitrogen-in-the-peconic-estuary/).

Consideration for RFP: As part of the RFP, a task should be included to allow HDR to add new subroutines to RCA for internal 2-way coupling of shellfish, SAV and seaweed sub-models within the ROMS-RCA IMF. Source code from old versions of RCA are available to develop sub-models for living resources as well as SAV and shellfish open-source code based on models developed for the Chesapeake Bay estuary model (Cerco and Moore 2001; Cerco and Noel 2007).

6.2 TAC Assessment of Local Embayment/Tidal River/Estuary Models

Task 3 of DEP's LR scope of work calls for local embayment/tidal river scale modeling. That is, for linking living resources models and existing embayment/tidal river hydrodynamic and water quality models (open boundary conditions to be extracted from system-wide LIS-HWQMS).

The ongoing LIS-HWQMS project includes a task to demonstrate 'proof of concept' that the system-wide ROMS-RCA model output can be used to provide open water boundary conditions as input for nested, finer-resolution hydrodynamic - water quality models of waterbodies such as an embayment or a tidal river/estuary. Based on the schedule for the ongoing LIS-HWQMS as shown in the QAPP (HDR, 2022), it is expected that a draft report of the fine-grid nested embayment models will be completed by February 2024. The nested fine-grid models will provide a demonstration of the calibration/validation of local-scale hydrodynamics and water quality conditions for two LI Sound embayments selected by HDR (Niantic River estuary, CT and Port Jefferson Harbor, NY). The nested fine-scale hydrodynamic and water quality response for the embayments will provide a demonstration of the combined impacts of (a) local-scale external forcing/ watershed loading; and (b) local-scale open water boundary response to (c) external forcing/watershed loading of the ROMS-RCA model at the system-wide scale. The system-wide model will provide a model framework that can be applied to support local embayment-scale evaluations of existing conditions for calibration and validation and future conditions for management scenarios for nutrients and climate change/sea level rise scenarios.

Recommendation #8: As described above, HDR plans on pilot-testing the linkage of the system-wide ROMS-RCA with nested, local-scale ROMS-RCA models of the Niantic River Estuary in Connecticut and Port Jefferson Harbor in Suffolk County, Long Island. Task 3 of DEP's Scope of Work for the Living Resource Modeling project requires pilot-testing of living resource models for selected local-scale embayments and tidal rivers/estuaries in Connecticut and Long Island. The TAC recommends that criteria considered for selection of candidate embayments or tidal rivers/estuaries for pilot-testing include the following requirements:

- An existing open source, public domain hydrodynamic and water quality model framework must be readily available for pilot-testing of living resource models;
- The existing model must be capable of accurately simulating observed spatial, temporal and vertical gradients of hydrodynamic and water quality state variables;
- The first step in the RFP is to start with habitat suitability for sessile organisms. Habitat Suitability Index analyses must have been performed and must be available as HSI maps for a candidate waterbody. Although water quality conditions may be acceptable, recent work in the Niantic River Estuary suggests that habitat suitability provides a better indicator of ecological conditions in a waterbody than does water quality.
- Observed data needed to setup, calibrate and validate living resource models must be available for the candidate waterbody for at least one of the three key species groups of living resources

(SAV, shellfish and seaweed). Data does not have to be available for all three groups of living resources for an embayment or tidal river/estuary to be considered a viable candidate for pilot-testing;

- If the available water quality model under consideration does not include living resource sub-models then source code or complete documentation of proposed methodology (equations, parameters, kinetic coefficients, etc.) for simulating living resource(s) must be available so that new code can be developed and tested in the selected water quality model to support coupling of living resources with the biogeochemical model.

The TAC recommends that the ROMS-RCA model of the Niantic River Estuary be considered as an ideal candidate for pilot testing the nested grid linkage of ROMS-RCA with living resource models. Under Recommendation #2 above, the TAC recommended that RCA be upgraded to incorporate living resource sub-models for SAV, seaweed and shellfish. A long-term historical data set (20+ years) for SAV and water quality observations in the Niantic River Estuary and the availability of Habitat Suitability Index assessments make this waterbody an excellent candidate for pilot-testing living resource models (see Figure 6-4). In addition, the Niantic River Estuary offers the opportunity for comparison of the effects and feedbacks among phytoplankton, macroalgae and/or macrophytes, and SAV production, water clarity, and nutrient cycling with ongoing estuarine modeling projects for the Niantic River estuary (e.g., Buzzelli et al. 1998, Brush and Nixon 2010, Vaudrey et al.).

The TAC is not currently aware of the availability of living resource data that would support development of living resource models for Port Jefferson Harbor. The TAC recommends, therefore, that an inventory of living resource data be compiled to support consideration of this embayment as a candidate for pilot-testing living resource models in a Long Island embayment.

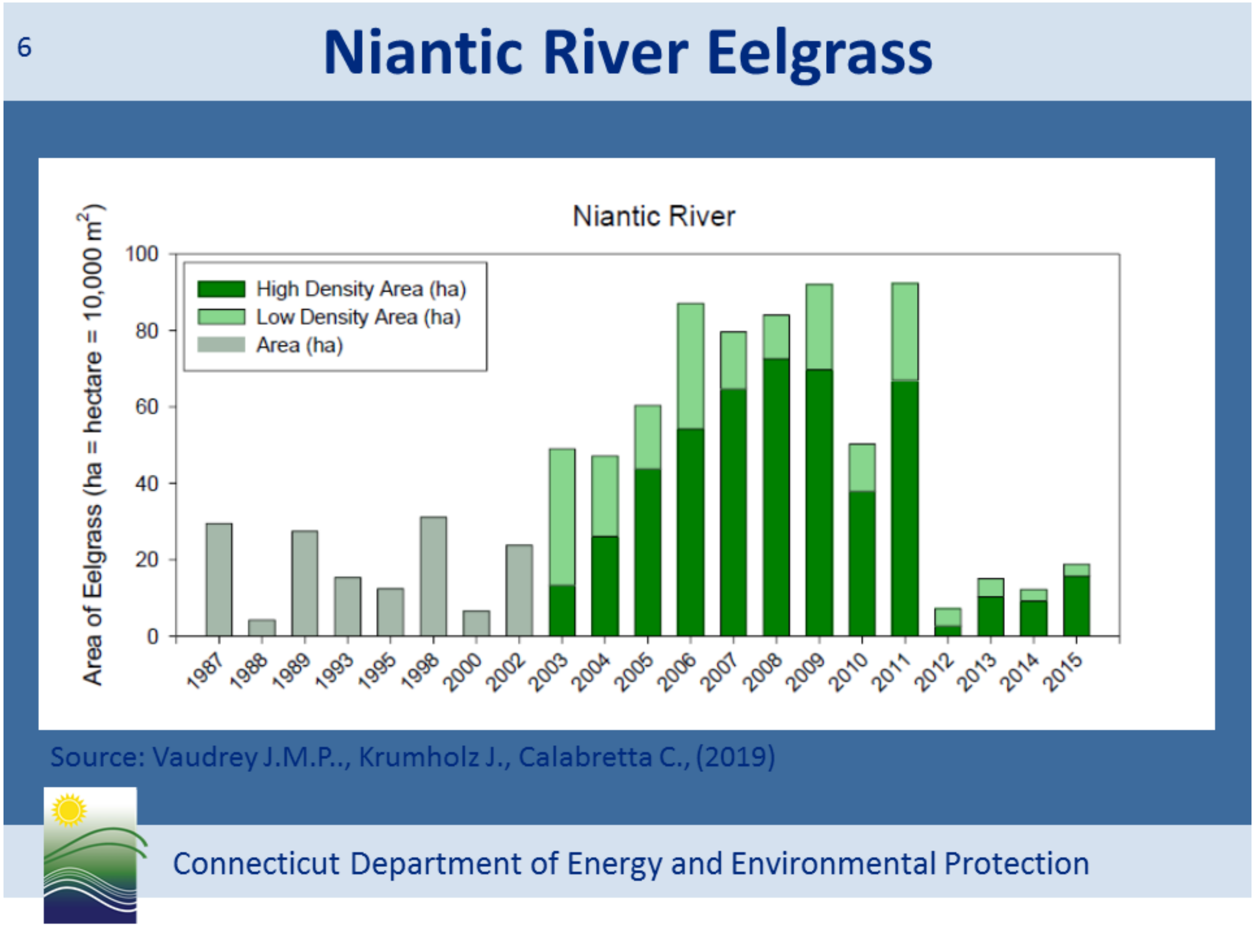

Figure 6-4 Long-Term Trend of Eelgrass in the Niantic River Estuary. Source: CTDEEP, Kelly Streich and Kate Knight, Presentation at TAC Workshop#3, November 10, 2022

<u>Recommendation #9</u>: In order to provide demonstrations of the mass balance-based impact of living resources on water quality and biogeochemical cycling within local-scale embayments or estuaries, the TAC recommends that living resource models should be internally coupled within the biogeochemical model of the embayment to provide 2-way feedback between living resources and water quality conditions. Dynamic biomass models of shellfish, SAV, and seaweed which are two-way coupled with the water quality/biogeochemical model can be used to evaluate changing estuarine conditions from watershed-based nutrient loading and climate change on the living resource production and distribution in the local-scale waterbodies over time, as well as evaluate the effect of shellfish, SAV and seaweed growth and distribution on nutrient cycling and primary productivity, DO, and water clarity within the local system.

There are examples of dynamic biomass models that are two-way coupled with biogeochemical models for shellfish (Bricker et al. 2018, Cerco and Noel 2005, 2007), SAV (Cerco and Moore 2001, Brush and Nixon 2010, Kalra et al. 2020), and seaweed (Broch and Slagstad 2012) described in Section 5 of this report. Several of the models discussed in Section 5 share similar functional parameters and rate equations that describe nutrient uptake, light availability, and temperature effects on SAV, phytoplankton and macrophyte or macroalgal photosynthesis. The functional parameters and rate equations for shellfish filtration of phytoplankton, shell growth and FARM-scale or population-level production, and respiration in relation to DO are often similar among the example shellfish models as well.

Develop, test, and validate dynamic biomass models of shellfish, SAV, and macroalgae and/or seaweed for 2-way coupling with the embayment or estuary-scale hydrodynamic and/or biogeochemical models. There are several examples of dynamic biomass models for the key living resources coupled within the biogeochemical or ecosystem framework for LIS or similar systems in Section 5 from which to apply within the nested, local-scale modeling framework for embayments, tidal rivers/estuaries and near coastal waters. The feedback between LR models and cycling of nutrients (N, P), Chl-a/POM or phytoplankton and water clarity or light availability, and DO should be accounted for within the coupled models for the embayments, tidal rivers/estuaries and near coastal waters.

Note that the dynamic biomass models for all three living resources could be internally coupled in the RCA water quality model and applied within the system-wide ROMS-RCA framework as described under Task 2. This approach was followed for earlier and similar living resource models in LI Sound (e.g., Bricker et al. 2018) and Chesapeake Bay (e.g., Cerco and Moore 2001, Cerco and Noel 2007).

The TAC recommends that living resource models should be open source code. This will allow the DEP project team to use and review, and integrate living resource models within the IMF. The TAC recommends that open source code be obtained for shellfish and SAV models developed for the Chesapeake Bay Environmental Modeling Program (CBEMP).

Recommendation #10 The TAC recommends that technical guidance be developed to ensure consistent linkage with the system-wide ROMS-RCA model for setup of nested fine-grid models for embayments, tidal rivers/ estuaries and nearshore coastal waters. The location of the open water boundary selected for linkage of the nested model with the system-wide ROMS-RCA model is a critical consideration for successful and accurate development of nested hydrodynamic/water quality models. Watershed discharge and contaminant tracer loading and tidal mixing processes must all be considered for selection of an appropriate open water boundary area in LI Sound. The open water boundary must be located far enough away in LI Sound from the outer region of an embayment or the mouth of a tidal river/estuary to ensure that measurable levels of contaminant tracers are negligible in the vicinity of the open water boundary. Selection of an appropriate open water boundary will ensure that linkage of the system-wide model with the nested, fine-grid model will provide an accurate simulation of tidal exchange processes that will not include measurable concentrations of any contaminant tracer discharged from the local watershed.

The GUI described in the next recommendation will ensure that ROMS-RCA output data is extracted consistently with user-specified depth and time averaging procedure within one, or more, user-defined open water boundary polygons. The technical guidance described under this recommendation will ensure that different stakeholder groups developing nested hydrodynamic, water quality and living resources models with output from the system-wide ROMS-RCA will have the information needed to identify open water boundaries and setup one or more polygons needed as input to the GUI.

Recommendation #11: Under ongoing LIS-HWQMS project, a GUI/DST is being developed to support pre- and post-processing tasks for the ROMS-RCA models (HDR, 2022). The TAC recommends that a tool be developed as part of the GUI to extract system-wide ROMS-RCA output data to provide open water boundary condition data formatted for input to nested hydrodynamic/water quality models of embayments, tidal rivers/estuaries and nearshore coastal waters. The spatial extent of an open water boundary area will be defined as input to the GUI using one or more user-specified polygons and ROMS-RCA output data will be extracted and post-processed with user-specified depth averaging and time-averaging intervals. The recommended GUI tool will be available to support nested, local-scale model applications for embayments, tidal rivers/estuaries or nearshore coastal waters under Task 3 and local-scale sites for modeling of bioextraction and "green" removal technologies under Task 4.

The GUI tool should initially be designed to extract and post-process output from ROMS-RCA and write open boundary condition data in the format required for input to a nested ROMS-RCA hydrodynamic and water quality model. Under the current work plan for the LIS-HWQMS (HDR, 2022), nested ROMS-RCA models of the Niantic River Estuary (CT) and Port Jefferson Harbor (NY) will be developed to pilot-test linkage of the system-wide ROMS-RCA model with nested ROMS-RCA models. As additional hydrodynamic and water quality models are selected by stakeholders for development of local-scale embayment models, the GUI tool will need to be updated to accommodate other hydrodynamic and water quality model data structures for open water boundary conditions data linkage to nested models. CTDEEP, for example, is currently planning development of local-scale hydrodynamic (EFDC) and water quality (WASP8) models for Norwalk Harbor (RESPEC, 2022).

Recommendation #12: Habitat Suitability and other Index models can provide very useful information about living resources without a mechanistic model. HSI models are widely used, often publicly available, easy to construct and test, and can be validated with observed monitoring data for species occurrence. Index models lack feedback with nutrient cycling or water quality conditions since this type of living resource model provides only 1-way coupling with physical characteristics and water quality conditions to predict habitat capacity or suitability to support a particular species such as SAV. There already exist published and validated habitat suitability models for LI Sound to help select sites suitable for shellfish and SAV and to evaluate their production potential into the future. The TAC recommends that local-scale nested, fine-grid hydrodynamic and water quality models of embayments, tidal rivers/estuaries and nearshore coastal waters can be very effectively used to provide input data to Habitat Suitability and other index models as a screening-level tool for living resources. Local-scale hydrodynamic and water quality model output can be driven by either existing historical conditions or future conditions based on management scenarios for nutrients and climate change/sea level rise. Habitat Suitability and other index models can thus provide a useful tool for screening-level evaluations of the effect of management scenarios on living resources.

Recommendation #13: EPA's "Nex-Gen" Strategy (USEPA, 2015) recommended that Numeric Nutrient Thresholds be established for embayments and nearshore waters, tributary watersheds, and coastal watersheds characterized by direct discharge of large wastewater treatment facilities. The TAC recommends that methodologies be developed to link watershed loading of nutrients with water quality and living resource responses to determine site-specific Numeric Nutrient Criteria/Thresholds to achieve water quality targets considered to be protective of designated uses. The restoration and maintenance of SAV is of particular importance for the LI Sound region.

Recommendation #14: It is well known that submerged obstacles can impact local-scale circulation and sedimentation processes in shallow water systems. Submerged obstacles that are living resources, such as shellfish and SAV, can account for a large area-based fraction of the thickness of the water column in shallow waters. The presence of these living obstacles causes reduced current speeds and wave dissipation that, in turn, influences nutrient uptake, rates of capture of particles and sediment, light attenuation and water clarity. The cause-effect sequence of interactions can then affect conclusions that may be drawn from water quality model simulations based on either calibration of observations to existing conditions or management scenarios. Although oyster reefs and SAV meadows may not alter system-wide large-scale flow patterns, these living resources certainly influence local-scale flow patterns. Oyster reefs, for example, have been proposed and developed in many coastal systems, including New York Harbor, as living "green infrastructure" to mitigate storm surge and prevent shoreline erosion (see NYSDEC, 2015). Oyster reefs have been shown to provide important benefits for coastal protection and restoration that could be modeled and used to justify mitigation and restoration projects. Ridge et al. (2015), for example, developed a model of oyster reef growth as a green infrastructure strategy to mitigate sea level rise along the southern Atlantic coast in North Carolina.

Consistent with EPA's "Nex-Gen" Strategy (EPA, 2015) described in Section 1, the ROMS-RCA model, coupled with living resource sub-models, provides DEP with the opportunity to link the effects of external loading, eutrophication and nutrient enrichment with ecological models to represent potential green infrastructure benefits of living resources, such as oyster reefs, to support planning efforts for coastal mitigation and restoration strategies.

The TAC recommends that 2-way feedback between hydrodynamics and living resources (see Figure 2-5 [C]) be incorporated where feasible for local-scale nested models of embayments, tidal rivers/estuaries and nearshore coastal waters. Kalra et al. (2020), for example, developed a ROMS-SAV model that explicitly simulated coupled 2-way feedback (see Figure 2-5 [D]) between SAV, hydrodynamics (velocity and waves), sedimentation dynamics, and water quality (nutrient cycling, light attenuation and water clarity). In contrast to Kalra's advanced approach, the TAC recommends a much simpler approach where the hydrodynamic model could be parameterized to account for living resource-dependent changes in bottom roughness and bathymetry. "Green" infrastructure strategies based on oyster reefs or seagrass meadows could then be modeled with a simplified approach that would allow approximations of the hydrodynamic effects of living resources without explicitly simulating the physical effects of oyster reefs or seagrass meadows as submerged obstacles to circulation processes.

Recommendation #15: In the shallow waters of embayments and tidal rivers/estuaries, continuous records of dissolved oxygen (DO) are typically characterized by a large diurnal range of DO. CTDEEP monitoring during the summer of 2022 in the Norwalk River at Ferry Point, for example, showed DO concentrations ranging from 0 to 20 mg/L and DO saturation ranging from 0 to supersaturation levels of 250 – 350% during the summer of 2022 (Figure 6-5). Large variability of DO concentration and DO saturation, such as the data for the Norwalk River, is controlled by physical, chemical and biological processes.

Water quality models that simulate nutrients and phytoplankton typically are not able to simulate wide ranges of diurnal DO. WASP models developed for Peconic Bay (WASP5: Tetra Tech, 1989) and Barnegat Bay (WASP8: Defne et al., 2017), for example, reproduced daily average DO but were not able to simulate the diurnal variability of DO because sub-surface photosynthetic production and respiration processes, such as seagrass and macroalgae, were not included in the water quality models. An analytical model of diurnal DO, however, showed that incorporation of sub-surface production and respiration from seagrass/macroalage was necessary to accurately model the observed diurnal range of DO in Peconic Bay (Tetra Tech, 1989; Morton et al., 1990). In addition to sub-surface production and respiration processes, Lung (2022: pages 162-166) showed that zooplankton needed to be included as a state variable in a eutrophication model of Loch Raven reservoir (Maryland) to accurately match observed supersaturation levels of DO. Simulation of algal biomass as Chl-a was also improved with the addition of herbivorous zooplankton to the eutrophication model.

As SAV and seaweed (macroalgae) will be modeled to pilot-test the linkage of nested local-scale hydrodynamic and water quality models with living resource sub-models, the TAC recommends that calibration and validation of the model must include model-data comparisons with high-frequency DO data where continuous monitoring records are available. Based on a comparison to diurnal DO data, pilot-testing of SAV or seaweed modeling may also possibly show that zooplankton may need to be considered to obtain accurate simulations of supersaturated DO conditions such as shown for the Norwalk River data set.

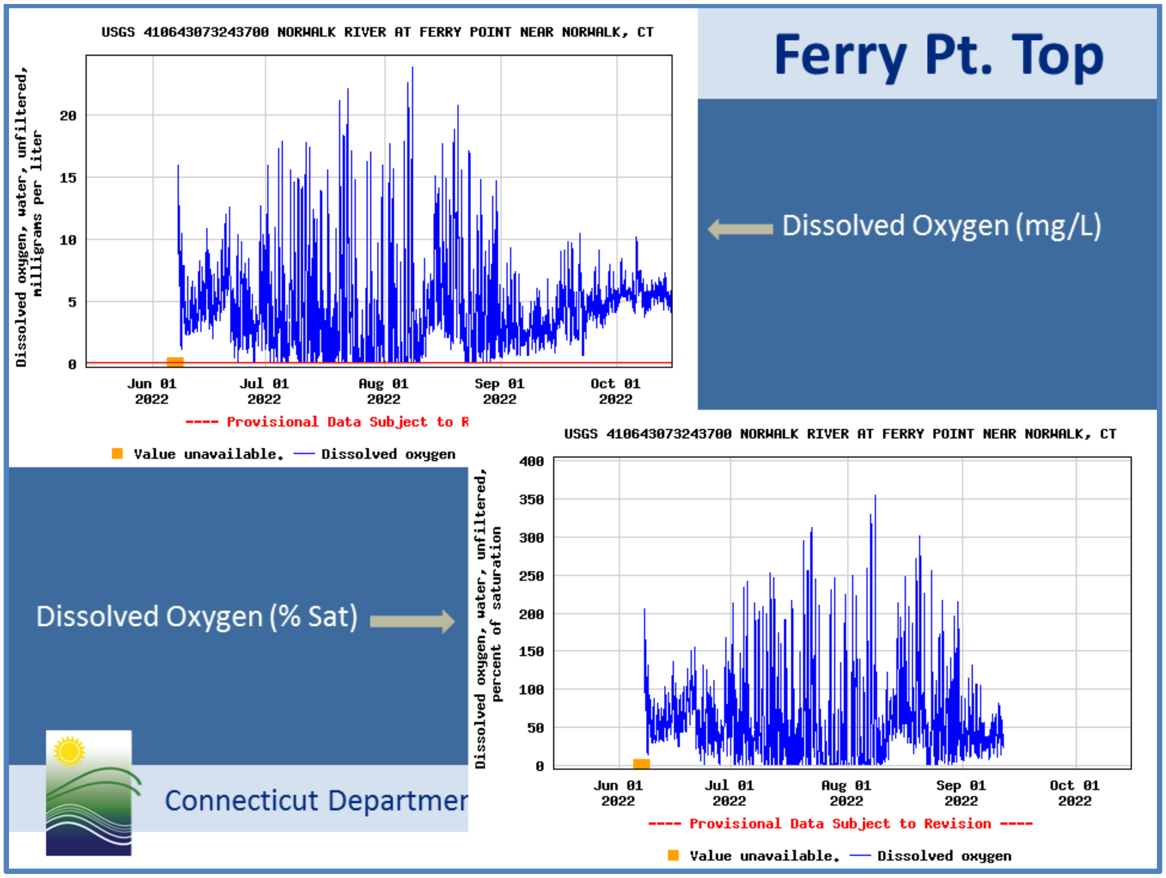

Figure 6-5 Continuous Monitoring of Top (Surface) Dissolved Oxygen in the Norwalk River at Ferry Point. Upper panel shows DO concentration and lower panel shows DO saturation. Source: CTDEEP, Kelly Streich and Kate Knight, Presentation at TAC Workshop#3, November 10, 2022

6.3 TAC Assessment of Bioextraction and “Green” Nitrogen Removal Strategies

Task 4 of DEP’s LR scope of work calls for identifying living resource models that facilitate answering management questions about bioextraction and “green” nitrogen removal strategies (the models will use LIS-HWQMS generated nutrient conditions under existing and future scenarios). Living resource biomass models will be used to evaluate ecosystem services assessments of bioextraction and “green” nitrogen removal technologies. The models will be used to support identification of suitable habitats for shellfish aquaculture sites and open water areas for seaweed/kelp farms and to quantify ecosystem services benefits. Estimates of nutrient removal rates and economic valuation of bioextraction and “green” technologies will be compared to the costs and benefits of conventional watershed-based “gray” technologies such as wastewater treatment facility upgrades and BMP strategies.

If biomass (fixed or dynamic) models for shellfish, SAV and seaweed/macroalgae are coupled with nutrient or biogeochemical models for either the system-wide scale (ROMS-RCA, Task 2) or at the local-scale for nested, fine-grid models of embayments, tidal rivers/estuaries or nearshore coastal waters (Task 3), then pilot testing of bioextraction capabilities and “green” technology nutrient removal strategies for all three key living resources can be performed for Task 4. The biomass models reviewed in in Section 5 and recommended by the TAC have already been used to evaluate the differential effects of shellfish, SAV, and/or seaweed farms on water clarity, light availability, nutrient cycling and eutrophication, changes in pelagic versus benthic production, as well as carbon sequestration and dissolved oxygen cycling within LI Sound, Chesapeake Bay, and other coastal systems.

Recommendation #16: Living resource biomass models should be used to evaluate ecosystem services assessments of bioextraction and "green" nitrogen removal technologies. Methodologies and approaches developed for ecosystem services assessments that provide estimates of nutrient removal rates and economic valuation of bioextraction and "green" technologies should be identified to support comparison of living resource benefits with conventional watershed-based "gray" technologies such as wastewater treatment facility upgrades and BMP strategies.

The system-wide ECOMSED-RCA model was used to support evaluations of the impact of living resources on *in-situ* nutrient removal in LI Sound for comparison to watershed-based nutrient reduction strategies. Bricker et al. (2015, 2018) used SWEM to link hydrodynamic and water quality output as input to EcoWin and FARM models that included shellfish growth to estimate in-situ removal of Chl-a and nutrients via shellfish production and harvest.

The TAC recommends that DEP use the system-wide ROMS-RCA model currently under development to update Bricker et al. (2015, 2018) ecosystem services assessments for LI Sound. Previous SWEM-based results were used as input to EcoWin and FARM model analyses to evaluate removal of phytoplankton biomass and nutrients by shellfish harvesting.

Recommendation #17: The two-way coupled biogeochemical models with the living resource biomass models developed for the system-wide ROMS-RCA and/or the local-scale embayment modeling framework should be used to specifically address how the living resource can affect nutrient cycling and bioextraction potential (C, N, P, Si), primary production and Chl-a or particulate organic matter and dissolved oxygen.

6.4 Section 6 References

Botero-Acosta, A., Darren L. Ficklin, Nima Ehsani, Jason H. Knouft (2022) Climate induced changes in streamflow and water temperature in basins across the Atlantic Coast of the United States: An opportunity for nature-based regional management, Journal of Hydrology: Regional Studies, Volume 44, 2022, 101202, ISSN 2214-5818, https://doi.org/10.1016/j.ejrh.2022.101202.

Bricker, S.B., J. Ferreira, C. Zhu, J. Rose, E. Galimany, G. Wikfors, C. Saurel, R. Landeck Miller, J. Wands, P. Trowbridge, R. Grizzle, K. Wellman, R. Rheault, J. Steinberg, A. Jacob, E. Davenport, S. Ayvazian, M. Chintala, and M. Tedesco. 2015. An Ecosystem Services Assessment using bioextraction technologies for removal of nitrogen and other substances in Long Island Sound and the Great Bay/Piscataqua Region Estuaries. NCCOS Coastal Ocean Program Decision Analysis Series No. 194. National Oceanic and Atmospheric Administration, National Centers for Coastal Ocean Science, Silver Spring, MD and United States Environmental Protection Agency, Office of Research and Development, Atlantic Ecology Division, Narragansett, RI. 154 pp + 3 appendices.

Bricker SB, Ferreira JG, Zhu C, Rose JM, Galimany E, Wikfors GH, Saurel C, Miller RL, Wands J, Trowbridge P, Grizzle RE, Wellman K, Rheault R, Steinberg J, Jacob AP, Davenport ED, Ayvazian S, Chintala M, and Tedesco MA 2018 The role of shellfish aquaculture in reduction of eutrophication in an urban estuary. Environmental Science & Technology 52 (1): 173–183. [PubMed: 28994282]

Brush MJ, Nixon SW. 2010. Modeling the role of macroalgae in a shallow sub-estuary of Narragansett Bay, RI (USA). Ecological Modelling 221: 1065-1079.

Burns, D.A., Gopal Bhatt, Lewis C. Linker, Jesse O. Bash, Paul D. Capel, Gary W. Shenk (2021) Atmospheric nitrogen deposition in the Chesapeake Bay watershed: A history of change, Atmospheric Environment, Volume 251, 2021, 118277, ISSN 1352-2310, https://doi.org/10.1016/j.atmosenv.2021.118277.

Buzzelli, C. P., R. L. Wetzel, M. B. Meyers. 1998. Dynamic Simulation of Littoral Zone Habitats in Lower Chesapeake Bay. II. Seagrass Habitat Primary Production and Water Quality Relationships. Estuaries, Vol. 21, No. 4, Part B (Dec., 1998), pp. 673-689

Cerco, C. and K. Moore, 2001. System-wide submerged aquatic vegetation model for Chesapeake Bay. Estuaries 24 (4), 522–534.

Cerco, C. and M. R. Noel, 2007. Can oyster restoration reverse cultural eutrophication in Chesapeake Bay? Estuaries and Coasts 30 (2), 331–343.

Cerco, C.F., and R. Tian. 2021. "Impact of Wetlands Loss and Migration, Induced by Climate Change, on Chesapeake Bay DO Standards. "Journal of the American Water Resources Association 1–13. https://doi.org/10.1111/1752-1688.12919

Defne, Zafer, Frederick J. Spitz, Vincent DePaul, and Tim A. Wool (*2017*) Toward a Comprehensive Water-Quality Modeling of Barnegat Bay: Development of ROMS to WASP Coupler. Journal of Coastal Research: Special Issue 78 - A Comprehensive Assessment of Barnegat Bay-Little Egg Harbor, New Jersey: pp. 34 – 45.

HDR (2022). Quality Assurance Project Plan (v. 2.0) Long Island Sound Hydrodynamic and Water Quality Modeling. Prepared for New York City Department of Environmental Protection, Bureau of Environmental Planning and Analysis, Flushing, NY. Prepared by Henningson, Durham & Richardson Architecture & Engineering, PC (HDR), New York, NY, August 22.

Hood, R. W. et al. (2021) The Chesapeake Bay program modeling system: Overview and recommendations for future development, Ecological Modelling, Volume 456, 2021, 109635, ISSN 0304-3800, https://doi.org/10.1016/j.ecolmodel.2021.109635.

HydroQual. 1995. SFWMD Wetlands Model. Prepared for South Florida Water Management District, West Palm Beach, FL by HydroQual, Inc., Mahwah, NJ, May.

HydroQual. 2002. A Water Quality Model for Jamaica Bay: Calibration of the Jamaica Bay Eutrophication Model (JEM), Final Report. Prepared under subcontract to O'Brien & Gere Engineers, Hawthorne, NY by HydroQual, Inc., Mahwah, NJ, June.

Kim JK, Kraemer GP, Yarish C (2015) Use of sugar kelp aquaculture in Long Island Sound and Bronx River Estuary for nutrient extraction. Mar. Ecol. Prog. Ser. 531:155–166.

Kim, J., M. Stekoll, C. Yarish. 2019. Opportunities, challenges and future directions of open-water seaweed aquaculture in the United States. Phycologia, 58:5, 446-461, DOI:10.1080/00318884.2019.1625611

Lung, W. (2022) *Water Quality Modeling that Works*, Springer-Link, https://dopi.org/10.1007/978-3-030-90483-8

Morton, M., A. Stoddard, and J. Pagenkopf (1990) Eutrophication and Nutrient Enrichment in the Peconic Estuary, Long Island: Numerical Model of Historical Conditions of the Mid-1970s, In: Spaulding, M. (ed), *Proceedings of ASCE Estuarine and Coastal Transport Modeling Conference*, Newport, RI, November 1989, pp. 351-360.

NYSDEC (2015) DEC RELEASES COASTAL GREEN INFRASTRUCTURE PLAN FOR NEW YORK CITY, P*lan Outlines How to Use Natural Features to Protect New York City, March 09, 2015,* https://apps.cio.ny.gov/apps/mediacontact/public/view.cfm?parm=FD961466-E15A-FC25-256BE47FF7185EF1)

O'Donnell, J. (2019) Sea Level Rise in Connecticut, Final Report, University of Connecticut, Dept. Marine Sciences and Connecticut Institute for Resilience and Climate Adaptation, February

Parker M, and Bricker S. 2020. Sustainable oyster aquaculture, water quality improvement, and ecosystem service value potential in Maryland Chesapeake Bay. Journal of Shellfish Research 39(2): 269-281.

PEP (2007) Total Maximum Daily Load for Nitrogen in the Peconic Estuary Program Study Area, Including Waterbodies Currently Impaired Due to Low Dissolved Oxygen: the Lower Peconic River and Tidal tributaries; Western Flanders Bay and Lower Sawmill Creek; and Meetinghouse Creek, Terrys Creek and Tributaries. Peconic Estuary Program (PEP), Suffolk County Dept. Health Services, Office of Ecology, Riverhead, NY, September.

RESPEC (2022) Norwalk Harbor Nutrient Modeling Plan, Topical Report RSI-3266, Prepared by RESPEC for Connecticut Dept. Energy and Environmental Protection, Hartford, CT, Project No. 4069.

Ridge, J. T. *et al.* (2015) Maximizing oyster-reef growth supports green infrastructure with accelerating sea-level rise. *Sci. Rep.* **5**, 14785; doi: 10.1038/srep14785 (2015), https://rdcu.be/c12e0

Testa, J.M., N. Basenback, C. Shen, K. Cole, A. Moore, C. Hodgkins, and D.C. Brady. 2021. "Modeling Impacts of Nutrient Loading, Warming, and Boundary Exchanges on Hypoxia and Metabolism in a Shallow Estuarine Ecosystem." Journal of the American Water Resources Association1–22. https://doi.org/10.1111/1752-1688.12912.

Tetra Tech (1989). Water Quality Modeling for the Peconic Bay BTCAMP. Interim Progress Report No. 2, Prepared for Dvirka & Bartilucci, Syosset, NY and Suffolk County Dept. Health Services, Riverhead, NY. Prepared by Tetra Tech, Inc., Fairfax, VA, August 31.

Tetra Tech (1999). Three-Dimensional Hydrodynamic and Water Quality Modeling of Peconic Estuary. Draft Final Report prepared for Peconic Estuary Program, Suffolk County Dept. Health Services, Riverhead, NY by Tetra Tech, Inc., Fairfax, VA.

Thuman, A. (2002) Personal communication Andrew Thuman (HDR) with Andrew Stoddard (Dynamic Solutions, LLC), December 14, 2022

Van Patten, M. A. (2015) "Seaweeds Clean Long Island Sound", Wrack Lines. 96. https://opencommons.uconn.edu/wracklines/96

7. TAC Recommendations for RFP Requirements

DEP should provide a link to TAC Living Resources report and recommend that proposal respondents use the TAC report to familiarize themselves with the living resources, existing model approaches, steps for model development and applications within LI Sound and similar coastal marine systems. Respondent's proposals will be able to make best use of the TAC's literature review and related information about living resources within their proposals.

7.1 RFP Requirements: Linkage of System-Wide Model with Nested, Fine-Grid Models

Table 7-1 RFP Requirements for linkage of system-wide model with nested, fine-grid models of embayments, tidal rivers/estuaries and nearshore coastal waters

RFP Requirements
Linkage with Regional System-Wide Model The system-wide ROMS-RCA model framework will be used to provide open water boundary conditions as input to nested, fine-grid local-scale hydrodynamic and water quality models of embayments, tidal rivers/estuaries and nearshore coastal waters.
The system-wide model will provide a model framework that can be applied to support local-scale evaluations of nested, fine-grid hydrodynamic/water quality models. Linkage of living resource models will be used to support impact assessments of living resources and water quality conditions.
Living resource models will be linked with the local-scale nested hydrodynamic and water quality model to support pilot-test assessments of the impact of living resources on water quality conditions under existing conditions for model calibration/validation and under future conditions based on nutrient management scenarios and climate change/sea level rise scenarios.
Management scenarios will be required to represent the potential effects of climate change and sea level rise on water quality and living resources. Detailed assessments of climate change and sea level rise impacts are not desirable for pilot-testing local-scale nested models. Screening-level approximations to climate change and sea level rise, however, are appropriate and should be described for pilot-testing local-scale nested models.
The first step in the RFP is to start with habitat suitability for sessile organisms. Habitat Suitability Index analyses must have been performed and must be available as HSI maps for a candidate pilot-test embayment, tidal river/estuary or other waterbody. Although water quality conditions may be acceptable, recent work in the Niantic River Estuary suggests that habitat suitability provides a better indicator of ecological conditions in a waterbody than does water quality.
The nested local-scale model must accurately account for the linkage of physical transport/mixing processes and water quality conditions with living resources at the spatial/temporal scale with acceptable goodness-of-fit for model performance necessary to accurately simulate water depth, water temperature, salinity, dissolved oxygen, nutrients, phytoplankton biomass, water clarity, light availability, and living resource biomass.
In addition to acceptable model results for daily average levels of DO, the nested local-scale model must also demonstrate good model-data agreement with high-frequency DO data where continuous DO monitoring records are available. Accurate modeling of the combined effects of net DO production by phytoplankton, SAV and/or seaweed, decomposition of organic matter and sediment oxygen demand on diurnal DO usually must be achieved to reproduce observed high variability of diurnal DO.

EPA's "Nex-Gen" Strategy (USEPA, 2015) recommended that Numeric Nutrient Thresholds be established for embayments and nearshore waters, tributary watersheds, and coastal watersheds characterized by direct discharge of large wastewater treatment facilities. Methodologies to link watershed loading of nutrients with water quality and living resource responses must be described to determine site-specific Numeric Nutrient Criteria/Thresholds to achieve water quality targets considered to be protective of designated uses. The restoration and maintenance of SAV is of particular importance for the LI Sound region.
Living resource models for shellfish and seaweed (macroalgae) must be able to accurately represent bioextraction strategies (e.g., oyster aquaculture) and "green" nitrogen removal strategies (e.g., sugar kelp farms). The living resource models must be able to quantify nutrient removal rates, the potential effectiveness and economic valuation of bioextraction and "green" technologies.
A methodology must be described for linkage of the system-wide ROMS-RCA model and setup and development of nested, fine-grid hydrodynamic and water quality models for embayments and tidal rivers and/or estuaries. The methodology needs to consider watershed discharge and contaminant "tracer" loading and tidal mixing processes as part of the rationale for selection of the location of the open water boundary area in LI Sound. The methodology must provide evidence that the open water boundary will be located far enough away from the outer area of an embayment or the mouth of a tidal river/estuary to ensure that measurable levels of contaminant tracers are negligible in the vicinity of the open water boundary. The methodology is needed to ensure that any stakeholder group developing a nested model with output from the ROMS-RCA system wide model follows an acceptable approach for extraction of system-wide hydrodynamic and water quality model results. This will ensure that linkage of the system-wide model with nested, fine-grid model will provide an accurate simulation of tidal exchange processes that will not include measurable concentrations of any contaminant tracer discharged from the local watershed.

7.2 RFP Requirements: Living Resource Models for Nested Fine-Grid Models

Table 7-2 RFP Requirements for pilot-testing local-scale living resource models linkage with nested, fine-grid models of embayments, tidal rivers/ estuaries and nearshore coastal waters

RFP Requirements
Local-Scale Living Resource Models for Nested Fine-Grid Models Living resource models are developed and linked with nested, fine-grid hydrodynamic and water quality models of embayments, tidal rivers/estuaries and nearshore coastal waters. Water quality and living resource models are used to determine site-specific Numeric Nutrient Criteria to achieve water clarity threshold targets for restoration of SAV.
Develop a living resource model that accurately represents physiological processes at an appropriate temporal and spatial scale and with acceptable goodness-of-fit for model performance necessary to simulate time-dependent living resource biomass and 2-way coupling of living resource with water quality conditions such as water clarity, light availability, nutrients, dissolved oxygen and phytoplankton biomass.
Living Resource modeling QAPP must be prepared
Identify processes that need to be included in LR model and provide conceptual model diagram of LR.

Identify required/desired LR model outputs and spatial/temporal resolution of LR model output. Identify/evaluate candidate LR models for selection of model to meet LR model objectives.
Identify Habitat Suitability and other types of index models as a screening-level tool for living resources that are available to support linkage with existing hydrodynamic and water quality models of embayments, tidal rivers/estuaries or nearshore coastal waters. Select Habitat Suitability or other index models to be used for linkage with living resources.
Identify existing calibrated/validated hydrodynamic and water quality models that are readily available to support linkage with living resource model for embayment, tidal river/estuary or nearshore coastal waters. Select hydrodynamic and water quality model to be used for linkage with living resources.
Identify data requirements needed for model setup, model calibration/validation and application of model for management scenarios. Identify data sources to support development of LR model. Compile data inventory assessment of data availability. Identify major data gaps and propose approach for filling in data gaps
Specify approach to be used for (a) linkage of LR model with local-scale hydrodynamic and water quality model; (b) pre-processing of data to develop model input files and observed data sets for model comparison; and (c) setup LR model with local-scale hydrodynamic/water quality model.
Specify approach and software tools to be used for (a) LR model calibration and validation; (b) visualization of LR model results; and (c) comparison of model results with observations.
Specify methods and performance targets to quantify model skill assessment.
Specify parameters to be tested and describe proposed approach to perform sensitivity and uncertainty analyses for LR models
Specify approach to be used for model evaluation of management scenarios for (a) nutrients and (b) climate change and sea level rise.
Specify approach to be used for determination of site-specific Numeric Nutrient Criteria/Thresholds to support LR
Technical reporting to document model selection, linkage/setup, results and key findings. Communication of LR model results to DEP, EPA, CTDEEP, NYSDEC and Stakeholders.
Technology transfer and model training for development of LR model and LR model code, input and output files, and documentation for application of LR model.

7.3 RFP Requirements: Living Resource Models for Bioextraction and "Green" Nitrogen Removal Technologies

Table 7-3 RFP Requirements for pilot-testing linkage of system-wide ROMS-RCA hydrodynamic and water quality with living resource models for evaluation of bioextraction and "green" nitrogen removal technologies

RFP Requirements
Local-Scale Living Resource Models for Bioextraction and "Green" Removal Technologies Living resource models are developed and linked with nested, fine-grid hydrodynamic and water quality models of embayments, tidal rivers/estuaries and nearshore coastal waters. Assess macroalgae (seaweed) and

shellfish for bioextraction, aquaculture and "green" technologies as Best Management Practices (BMPs) for *in-situ* nutrient management strategies;
Develop a living resource model that accurately represents physiological processes at an appropriate temporal and spatial scale and with acceptable goodness-of-fit for model performance necessary to simulate time-dependent living resource biomass and 2-way coupling of living resource with water quality conditions such as water clarity, light availability, nutrients, dissolved oxygen and phytoplankton biomass.
Living resource models for shellfish and seaweed (macroalgae) must be able to accurately represent bioextraction strategies (e.g., oyster aquaculture) and "green" nitrogen removal strategies (e.g., sugar kelp farms). The living resource models must be able to quantify nutrient removal rates, implementability, and economic valuation of "green" technologies to provide comparison to nutrient removal rates and costs of "gray" technologies.
Living Resource modeling QAPP must be prepared
Identify processes that need to be included in LR model and provide conceptual model diagram of LR physiological or biogeochemical processes needed for evaluation of nutrient removal rates and potential effectiveness of bioextraction and "green" technologies. Identify required/desired (a) LR model outputs and (b) spatial/temporal resolution of LR model output and identify and evaluate candidate LR models for selection of model to meet LR model objectives.
Specify spatial areas of embayments, tidal rivers/estuaries or coastal waters of LI Sound to be evaluated for aquaculture operations or seaweed/kelp farms.
Identify (a) data requirements needed for model setup, model calibration/validation and application of LR models for management scenarios; and (b) data sources to support development of LR model.
Compile data inventory assessment of data availability and identify major data gaps and propose approach for filling in data gaps
Specify approach and software tools to be used for: (a) linkage of LR model with either system-wide or local-scale hydrodynamic and water quality model; (b) pre-processing of data to develop model input files and observed data sets for model comparison; and (c) setup of LR model
Specify approach and software tools to be used for post-processing of data to support (a) LR model calibration/validation; (b) visualization of LR model results; and (c) comparison of model results with observations.
Specify methods, software tools and performance targets to quantify model skill assessment.
Specify parameters to be tested, software tools and describe proposed approach to perform sensitivity and uncertainty analyses for LR models
Specify approach to be used for model evaluation of management scenarios for (a) nutrients and (b) climate change and sea level rise.
Specify approach to be used for evaluation of (a) nutrient removal rates and (b) potential effectiveness of bioextraction and "green" technologies.
Specify approach to be used for evaluation of economic valuation of bioextraction and "green" technologies.

Technical reporting to document model selection, linkage/setup, results and key findings. Communication of LR model results to DEP, EPA, CTDEEP, NYSDEC and Stakeholders.
Technology transfer and model training for development of LR model and LR model code, input and output files, and documentation for application of LR model.

7.4 Section 7 References

USEPA (2015) Evolving the Long Island Sound Nitrogen Reduction Strategy, US Environmental Protection Agency, December 2015. US Environmental Protection Agency, Region 1 (Boston, MA) and Region 2 (New York City, NY). December. https://longislandsoundstudy.net/wp-content/uploads/2016/02/LIS-Nitrogen-Strategy-Enclosures-12-23-15-1.pdf

8. TAC Recommendations for RFP Respondents

DEP should provide a link to TAC Living Resources report and recommend that proposal respondents use the TAC report to familiarize themselves with the living resources, existing model approaches, steps for model development and applications within LI Sound and similar coastal marine systems. Respondent's proposals will be able to make best use of the TAC's literature review and related information about living resources within their proposals.

8.1 Respondent Requirements: Linkage of System-Wide Model with Nested, Fine-Grid Models

Table 8-1 Respondent Requirements for linkage of system- wide model with nested, fine-grid models of embayments, tidal rivers/estuaries and nearshore coastal waters

Respondent Requirements
Linkage with Regional System-Wide Model The system-wide ROMS-RCA model framework will be used to provide open water boundary conditions as input to nested, fine-grid local-scale hydrodynamic and water quality models of embayments, tidal rivers/estuaries and nearshore coastal waters.
Respondents demonstrate knowledge and experience with ROMS and other hydrodynamic models used for coastal ocean and estuarine applications
Respondents demonstrate knowledge and experience with RCA and other water quality or biogeochemical models used for coastal ocean and estuarine applications
Respondents demonstrate knowledge and coastal-estuarine experience with linkage of large-scale hydrodynamic and water quality/biogeochemical models to provide open water boundary input to smaller scale nested hydrodynamic and water quality/biogeochemical models
Respondents demonstrate system-wide understanding of the LI Sound-NY Harbor-NY Bight coastal-estuarine system with a conceptual model description of the key physical and biogeochemical processes that control dissolved oxygen, nutrient cycling, phytoplankton production and the interaction between water quality conditions (e.g., dissolved oxygen, water clarity, light availability) and ecological processes for SAV, seaweed/kelp and shellfish at local-scales of embayments, tidal rivers/estuaries and nearshore waters.
Respondents demonstrate understanding of the difference between system-wide simulations based on existing historical conditions for model calibration/validation and system-wide simulations based on future conditions under nutrient management scenarios and climate change/sea level rise scenarios.
Respondent demonstrate understanding of why consistent technical approaches are needed for linkage of system-wide large-scale model to ensure accurate development of nested, fine-grid models for embayments, tidal rivers/estuaries, and nearshore coastal waters.
Respondent demonstrate understanding of why the location for extraction of system-wide hydrodynamic and water quality model results for specification of open water boundary conditions is a critical issue for linkage of system-wide large-scale model to develop nested, fine-grid models of embayments, tidal rivers/estuaries and nearshore coastal waters.

8.2 Respondent Requirements: Living Resource Models for Nested Fine-Grid Models

Table 8-2 Respondent Requirements for pilot-testing local-scale living resource models linkage with nested, fine-grid models of embayments, tidal rivers/ estuaries and nearshore coastal waters

Respondent Requirements
Local-Scale Living Resource Models Living resource models are developed and linked with nested, fine-grid hydrodynamic and water quality models of embayments, tidal rivers/estuaries and nearshore coastal waters. Water quality and living resource models are used to determine site-specific Numeric Nutrient Criteria to achieve water clarity threshold targets for restoration of SAV.
Respondent demonstrates understanding of available methodologies to determine site-specific Numeric Nutrient Criteria Thresholds to achieve water quality targets considered to be protective of designated uses for coastal-estuarine systems. The restoration and maintenance of SAV is of particular importance for the LI Sound region.
Respondent demonstrates understanding of how living resources such as shellfish, SAV and seaweed (macroalgae) can influence local-scale water quality conditions such as water clarity, light availability, nutrient cycling, dissolved oxygen, particulate organic matter, and phytoplankton biomass.
Respondent demonstrates understanding of how shellfish and seaweed (macroalgae) can be used to evaluate ecosystem services and nutrient removal rates of bioextraction strategies (e.g., oyster aquaculture) and “green” nitrogen removal strategies (e.g., sugar kelp farms).
Respondent demonstrates understanding of how shellfish and seaweed (macroalgae) can be used to evaluate economic valuation benefits of bioextraction strategies (e.g., oyster aquaculture) and “green” nitrogen removal strategies (e.g., sugar kelp farms).
Respondent demonstrates understanding of the types of living resource models that could be used for the LI Sound project and demonstrates experience reviewing/evaluating strengths and weaknesses of living resource models and providing justification for selection of related living resource model approaches.
Respondent demonstrates knowledge of EPA Guidance for QAPPs for Modeling and experience with preparation of modeling QAPP’s including QAPP’s that specifically describe development of living resource and ecological models.
Respondent demonstrates understanding of output data needed and appropriate spatial and temporal resolution for local-scale simulation of living resources.
Respondent demonstrates knowledge of, and experience with, applications of living resource models for coastal-estuarine systems in LI Sound region and other similar marine environments.
Respondent demonstrates knowledge of, and experience with, applications of Habitat Suitability and other types of index models as a screening-level tool for living resources that are available to support linkage with existing hydrodynamic and water quality models of embayments, tidal rivers/estuaries or nearshore coastal waters.
Respondent demonstrates knowledge of, and experience with, existing calibrated and validated hydrodynamic and water quality models that are readily available to support linkage with living resource models for embayments, tidal river/estuary or nearshore coastal waters

Respondent demonstrates knowledge of, and experience with, Habitat Suitability or other index model for linkage with existing calibrated and validated fine-grid hydrodynamic and water quality model.
Respondent demonstrates knowledge of, and experience with, existing calibrated and validated fine-grid hydrodynamic and water quality models that are available in the public domain as an open source model for linkage with living resource model.
Respondent must demonstrate that selected fine-grid model has sufficient grid resolution in shallow water areas to accurately resolve water depth and light attenuation needed for the SAV model and to derive Numeric Nutrient Criteria/Thresholds to meet SAV water clarity targets for light availability.
If Respondent determines that resolution of the selected fine-grid model is not adequate to accurately resolve depth and/or light attenuation then Respondent must propose an approach for refinement of the existing grid to achieve adequate spatial and vertical resolution of the fine-grid model.
Respondent demonstrates knowledge of, and experience with, obtaining secondary data from various data sources to support development of living resource models.
Respondent demonstrates experience with compilation of data inventory for assessment of data availability, identification of data gaps and methods used to fill in data gaps for living resource models.
Respondent describes approach to be used for linkage of living resources model with local-scale hydrodynamic and water quality model. Respondent identifies linkage of living resource model as either 1-way or 2-way coupling with water quality model.
Respondent demonstrates knowledge of, and experience with modification of source code for RCA water quality model and other water quality/biogeochemical models. Respondent demonstrates experience with incorporating living resource sub-models in RCA model and other water quality/biogeochemical models.
Respondent demonstrates knowledge of, and experience with pre-processing of data to develop model input files and observed data sets for living resource model comparison. Respondent demonstrates knowledge of, and experience with setup and execution of living resource models.
Respondent demonstrates knowledge of, and experience with living resource model calibration and validation. Respondent describe approach and/or software tools used for visualization of living resource model results and comparison with observations.
Respondent demonstrates knowledge of, and experience with model performance assessments. Respondents proposes approach to be used to quantify model skill assessment to meet model performance targets.
Respondent demonstrates knowledge of, and experience with sensitivity and uncertainty analyses for living resource models and proposes approaches to perform sensitivity and uncertainty analyses.
Respondent demonstrates understanding of, and experience performing living resource model evaluations of management scenarios including scenarios for nutrients and climate change/sea level rise.
Respondent demonstrates understanding and experience with methodologies to determine site-specific Numeric Nutrient Criteria/Thresholds to achieve water quality targets to meet designated uses. Respondent proposes approach to determine site-specific Numeric Nutrient Criteria/Thresholds to support SAV as restoration of SAV meadows is of particular importance for the LI Sound region.

Respondent demonstrates experience with technical reporting to document model selection, linkage/setup, results and key findings and communication of living resource model results to Stakeholders and state, local and federal agencies such as DEP, CTDEEP, NYSDEC, NOAA and EPA.
Respondent demonstrates experience with technology transfer and model training for development of living resource models, model code, input and output files, and documentation for applications of living resources model.

8.3 Respondent Requirements: Living Resource Models for Bioextraction and "Green" Nitrogen Removal Technologies

Table 8-3 Respondent requirements for pilot-testing linkage of system-wide ROMS-RCA hydrodynamic and water quality with living resource models for evaluation of bioextraction and "green" nitrogen removal technologies

Respondent Requirements
Local-Scale Living Resource Models Living resource models are developed and linked with nested, fine-grid hydrodynamic and water quality models of embayments, tidal rivers/estuaries and nearshore coastal waters. Assess macroalgae (seaweed) and shellfish for bioextraction, aquaculture and "green" technologies as Best Management Practices (BMPs) for *in-situ* nutrient management strategies;
Respondent demonstrates understanding of how living resources such as shellfish, SAV and seaweed (macroalgae) are used for bioextraction strategies (e.g., oyster aquaculture) and "green" nitrogen removal strategies (e.g., sugar kelp farms).
Respondent demonstrates understanding of the types of living resource models that could be used for the LI Sound project and demonstrates experience reviewing/evaluating strengths and weaknesses of living resource models and providing justification for selection of related living resource model approaches.
Respondent demonstrates understanding of how living resource models are used to quantify nutrient removal rates for "green" technologies to provide comparison to nutrient removal rates and benefits of "gray" technologies.
Respondent demonstrates understanding of how living resource models are used to quantify economic valuation of "green" technologies to provide comparison to costs and benefits of "gray" technologies.
Respondent demonstrates knowledge of EPA Guidance for QAPPs for Modeling and experience with preparation of modeling QAPP's including QAPP's that specifically describe development of living resource and ecological models.
Respondent demonstrates understanding of output data needed and appropriate spatial and temporal resolution for local-scale simulation of living resources for bioextraction with aquaculture operations for shellfish and seaweed/kelp farms.
Respondent demonstrates knowledge of, and experience with, applications of living resource models for coastal-estuarine systems in LI Sound region and other similar marine environments. Respondent demonstrates specific knowledge of, and experience with, applications of shellfish and seaweed/kelp models for bioextraction and "green" technologies in LI Sound region and other similar marine environments.

Respondent demonstrates knowledge of, and experience with, bioextraction and "green" technologies for nutrient management including living resource models used to simulate aquaculture operations for oysters and other shellfish and seaweed/kelp farms.
Respondent proposes spatial area within the coastal waters of LI Sound to be evaluated for aquaculture operations or seaweed/kelp farms.
Respondent demonstrates knowledge of, and experience with obtaining secondary data from various data sources to support development of living resource models.
Respondent demonstrates experience with compilation of data inventory for assessment of data availability, identification of data gaps and methods used to fill in data gaps for living resource models.
Respondent describes approach to be used for linkage of living resources model with local-scale observed data or output from hydrodynamic and water quality model. Respondent identifies linkage of living resource model as either 1-way or 2-way coupling with water quality or water quality model.
If respondent proposes to modify biogeochemical model source to incorporate living resource sub-model for assessment of bioextraction and "green" technologies, then respondent must demonstrate knowledge of, and experience with modification of source code for biogeochemical models and respondent must demonstrate experience incorporating living resource sub-models into existing biogeochemical models.
Respondent demonstrates knowledge of, and experience with pre-processing of data to develop model input files and observed data sets for living resource model comparison. Respondent demonstrates knowledge of, and experience with setup and execution of living resource models.
Respondent demonstrates knowledge of, and experience with living resource model calibration and validation. Respondent describe approach and/or software tools used for visualization of living resource model results and comparison with observations.
Respondent demonstrates knowledge of, and experience with model performance assessments. Respondents proposes approach to be used to quantify model skill assessment to meet model performance targets.
Respondent demonstrates knowledge of, and experience with sensitivity and uncertainty analyses for living resource models and proposed approaches to perform sensitivity and uncertainty analyses.
Respondent demonstrates understanding of, and experience performing living resource model evaluations of management scenarios including scenarios for nutrients; climate change/sea level rise.
Respondent demonstrate understanding of, and experience with methodologies to evaluate nutrient removal rates, potential effectiveness and economic valuation of bioextraction and "green" technologies. Respondent proposes approach to be used for evaluation of nutrient removal rates and economic valuation of bioextraction and "green" technologies.
Respondent demonstrates experience with technical reporting to document model selection, linkage/setup, results and key findings and communication of living resource model results to Stakeholders and state, local and federal agencies such as DEP, CTDEEP, NYSDEC, NOAA and EPA.
Respondent demonstrates experience with technology transfer/model training for living resource models, model code, I/O files, and documentation for applications of living resources model.

9. Biographies of TAC Members

TAC Members for Living Resources

TAC Members and Affiliation
Andrew Stoddard (*) Chair, Dynamic Solutions, LLC
Lewis Linker (*) CBP Modeling Coordinator, EPA Chesapeake Bay Program Office
Suzanne Bricker (*) Physical Scientist, NOAA NOS NCCOS, Oxford Laboratory
Julie Rose (*) Research Ecologist, NOAA Fisheries, NEFSC Milford Laboratory
Kristin Kraseski (*) Bioextraction Coordinator, NYS DEC and NEIWPCC
Shaye Sable, Project support, Dynamic Solutions, LLC

TAC member biographies are presented in the following pages in this section.

Andrew Stoddard, Ph.D. astoddard@dsslc.com

Affiliation: Dynamic Solutions, LLC, Knoxville, TN

Andy Stoddard is a nationally known water quality modeler with over 40 years of experience. He has a Bachelor's in Civil Engineering and a Master's in Environmental Engineering & Science from Manhattan College in New York City and he earned his Ph.D. in Environmental Engineering & Science from the University of Washington in Seattle. His projects have included numerous assessments of physical and biogeochemical processes that control nutrient enrichment, oxygen depletion, eutrophication, and Harmful Algal Blooms (HABs) including studies in the Long Island Sound area. His doctoral research at Brookhaven National Laboratory included oceanographic research cruises to collect data to support development of a hydrodynamic and water quality model to investigate the effect of physical forcing on the 1976 anoxic event off the NJ coast. He developed eutrophication models of Peconic Bay and Norwalk Harbor (CT) to support nutrient loading evaluations and he investigated the role of wind forcing on the occurrence of anoxic conditions and "Green Tide" bloom events off the NJ coast.

He has provided technical review support for eutrophication modeling studies including the USACE *New York Bight Feasibility Study* and NYC DEP's *Technical Advisory Committee for Long Island Sound Hydrodynamic and Water Quality Modeling Study.* He is currently serving on the Model Evaluation Group (MEG) for NYC DEP's *Long Island Sound Hydrodynamic and Water Quality Modeling Study* and he has previously served on MEG's for NJ DEP's *Barnegat Bay – Little Egg Harbor Estuary Eutrophication Model* and EPA's *New York Bight Restoration Study*.

Based near Leesburg in Northern Virginia, Andy has been working with Dynamic Solutions, LLC since 2002 and he has been teaching graduate-level courses in surface water modeling and monitoring at Johns Hopkins University in the Whiting School of Engineering since 2003. His interest in environmental science and aquatic ecology undoubtedly was influenced by growing up on Staten Island where he was surrounded by woods, fields, hills, marshes, and beaches on the South Shore of the most rural borough of New York City.

Lewis Linker Linker.Lewis@epa.gov

Affiliation: EPA, Chesapeake Bay Program Office, Annapolis, MD

Lewis Linker is the Chesapeake Bay Program's Modeling Coordinator and Team Leader for Science and Analysis in SAIB (CBP's Science, Analysis, and Implementation Branch). Lew works with colleagues in the six CBP States of the Chesapeake watershed to develop linked models of the airshed, watershed, estuary, and living resources of the Chesapeake. The linked models of the Chesapeake have provided the basis for the nutrient and sediment reductions in the historic 2010 Chesapeake TMDL and the ecological restoration of the Chesapeake watershed and tidal waters. The nutrient and sediment allocations Chesapeake TMDL will reduce Chesapeake nutrient and sediment loads by about a half and one third, respectively, from the high point of nutrient and sediment loading in the mid-1980's.

Lew regularly provides national and international guidance, advice, and assistance on environmental models of coastal watersheds. He and his team have received more than nineteen major awards including two Smithsonian Awards in information technology excellence, the Horner Award from the American Society of Civil Engineers, the American Water Resources Association's Boggess Award, the 2022 IAAA Best Paper Award, four EPA Gold Medals, four Bronze Medals, and two major EPA awards for scientific achievement. Lew received his Masters from the Johns Hopkins Whiting School of Engineering. His abiding professional interest is in the expansion and refinement of current watershed, airshed, and estuarine models of the Chesapeake, and in improving the capabilities and utility of linked water quality and living resource models everywhere. Lew Linker has authored more than 200 reports, book chapters, and peer reviewed papers. Lew and his wife Julie live in Annapolis, Maryland and have two boys and four grandchildren.

Suzanne Bricker, Ph.D. suzanne.bricker@noaa.gov

Affiliation: NOAA NCCOS Cooperative Oxford Lab, Oxford, MD

Suzanne Bricker, a Physical Scientist at NOAA's National Ocean Service Cooperative Oxford Laboratory, is internationally known for her 30+ years of research evaluating the impacts of and developing solutions to address eutrophication in coastal waters. She is lead for NOAA's National Estuarine Eutrophication Assessment and the National Center for Coastal Ocean Science Lead for oyster ecosystem services. She earned a BA from Northwestern University and a PhD from the University of Rhode Island, Graduate School of Oceanography. Her collaborators include national and international modelers, economists, the aquaculture industry, academic researchers, and federal, state, and local environmental managers. Her current research focuses on nutrient removal ecosystem services provided by bivalve shellfish (oysters, clams) to inform marine policy on spatial planning and development and application of successful innovative nutrient management measures.

She and partners developed the Assessment of Estuarine Trophic Status (ASSETS; www.eutro.org/register) model to evaluate impacts of nutrient pollution that has been applied extensively in the US, Europe, and China. More recently her research has focused on the use of bivalve shellfish aquaculture to reduce nutrient impacts while providing a sustainable source of seafood. She and international partners developed the Farm Aquaculture Resource Management model (FARM; www.farmscale.org) for estimation of production and the nutrient removal service provided by farmed bivalve shellfish that has been applied in the US and elsewhere. This research supports seafood production and protection of coastal water quality and includes estimation of the economic value of these services to inform development of nutrient credit trading programs.

She was a member of the European Union Eutrophication Task Group working toward successful implementation of the European Water Framework and Marine Strategy Framework Directives. Her publication on development of the FARM model was named the Number 5 hottest article in *Aquaculture* in June 2007. She has been a member of the Chesapeake Bay Oyster BMP Scientific Expert Panel since 2015. She is the recipient of two NOAA Administrator's Awards for groundbreaking study and scientific leadership in understanding of coastal eutrophication, and a NOAA Administrator's Award with Dr. Julie Rose for research leading to the approval in Chesapeake Bay of the use of oysters as an innovative nutrient mitigation measure.

Julie Rose, Ph.D. julie.rose@noaa.gov

Affiliation: NOAA NMFS Laboratory, Milford, CT

Julie Rose is a Research Ecologist with the NOAA Fisheries NEFSC Milford Laboratory. She leads an applied research program studying interactions between shellfish aquaculture and the natural environment. Her work resides at the intersection of science and resource management, and supports a variety of stakeholders in the aquaculture community, including regulators, industry members, policymakers, and extension agents. Her current research program is focused on quantifying nutrient reduction and habitat provisioning services by shellfish aquaculture operations in the United States, and working with resource managers to incorporate this information into regulatory frameworks for nutrients, fish habitat, and aquaculture permitting.

Julie regularly provides scientific advice and technical assistance to resource management at the state and federal level. She has been a member of the Long Island Sound Science and Technical Advisory Committee since 2009. Julie is currently the Chair of the Technical Advisory Committee for the USDA Northeast Regional Aquaculture Center, and has been the Connecticut representative to that committee since 2018. Julie has also been a member of the Chesapeake Bay Oyster BMP Scientific Expert Panel since 2015.

Julie has received regional and national recognition for her research efforts. She has received the NOAA Judith Brennan-Hoskins Memorial award for excellence in research within the Northeast Region. She was part of a team that received the Northeast Sea Grant Outstanding Group Outreach award for development of the CT Shellfish Initiative. She received the national NOAA Administrator's Award, with colleague Suzanne Bricker, for innovative research and service as experts, leading to the approved use of oysters as a means of mitigating nutrients in the Chesapeake Bay.

Julie earned her Ph.D. in Marine Environmental Biology from the University of Southern California, and was awarded a postdoctoral fellowship from the National Science Foundation to conduct research at the Woods Hole Oceanographic Institution. She served as the Science Coordinator and NOAA liaison to the Long Island Sound Study for several years prior to joining the Milford Lab in 2011.

Kristin Kraseski, Ph.D. Kristin.Kraseski@dec.ny.gov

Affiliation: NEIWPCC and the New York State Department of Environmental Conservation

Kristin Kraseski, an Environmental Analyst with New England Interstate Water Pollution Control Commission (NEIWPCC), is based out of the Region 1 office of the New York State Department of Environmental Conservation (NYS DEC) in Stony Brook, NY. She has a Master's in Environmental Studies from Long Island University and earned her Ph.D. in Forest Resources and Hydrology from the University of Georgia in Athens. She has worked on nutrient pollution issues in coastal waters in and around New York for the last six years, with the last 2.5 years focused on the benefits of 'bioextraction' as a nitrogen removal strategy. She works on the Long Island Sound Nutrient Bioextraction Initiative, which is funded through EPA's Long Island Sound Study, in collaboration with NEIWPCC and NYS DEC. The Initiative aims to improve water quality in New York and Connecticut's marine and coastal waters by removing excess nitrogen through the growing and harvesting of shellfish and seaweed, and addressing the technical, regulatory, and economic challenges facing the development of a 'bioextraction' industry within Long Island Sound.

Shaye Sable, Ph.D. ssable@dsllc.com

Affiliation: Dynamic Solutions, LLC, Baton Rouge, LA

Shaye Sable is an aquatic/fisheries biologist and ecological modeler with 22 years of experience developing and applying population, community, and food web models to evaluate population and ecosystem responses to changing environmental conditions, habitat, and stressors such as invasive species and exposure to toxicants. She earned her Ph.D. in Oceanography & Coastal Sciences from Louisiana State University and B.S. degree in Biology from Ohio State University. She has linked her models to time series of environmental data, hydrodynamic models and water quality models to explore how aquatic populations and food webs respond to freshwater river diversions, hypoxia and contaminants, habitat restoration and degradation. Dr. Sable has developed statistical analyses and models to describe long-term environmental and biological data, as well as complex, process-based ecological models of aquatic species and ecosystems throughout the United States, with most of her work along the Louisiana coast.

Dr. Sable has provided scientific guidance, expert opinions, data analyses and review, as well as numerical modeling for operations and alternatives analyses, in order to support federal and state project teams on Biological Assessments, Environmental Assessments and Environmental Impact Statements, Management and Adaptive Management Plans related to freshwater and sediment diversions, oyster reef and wetland restoration projects, water resource projects and oil spill damage assessment. She serves as an expert panel reviewer for the U.S. Army Corps of Engineers and supports litigation involving ecological impacts determination and aquatic assessments of water resource, restoration and protection projects.

10. Attachments to TAC Report

The following attachments are provided as a separate companion document to the Living Resources TAC final report. The attachments are related to the Living Resources TAC, the final TAC report, and the online TAC meetings.

Attachment 1 – DEP Draft Scope of Work for Living Resources	(2019)	[7 pages]
Attachment 2 – Kick-off Meeting Agenda and Presentation	(Aug-24-2022)	[18 pages]
Attachment 3– TAC Workshop #1 Agenda and Presentation	(Sept-20-2022)	[19 pages]
Attachment 4 – TAC Workshop #2 Agenda and Presentation	(Oct-13-2022)	[22 pages]
Attachment 5 – TAC Workshop #3 Agenda and Presentation	(Nov-10-2022)	[40 pages]
Attachment 6 – TAC Team Responses to Questions about Living Resource Models		[18 pages]

Technical Advisory Committee

Living Resources for Long Island Sound Integrated Model

<u>## END FINAL REPORT ##</u>