Hydrodynamic & Water Quality Model Selection and Setup

New York City Department of Environmental Protection

DEP LIS-HWQMS Project

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Acronyms

A2EM	Advanced Aquatic Ecosystem Model
AdH	Adaptive Hydraulics Model
AESOP	Advanced Ecological Systems Modeling Program
CARP	Contaminant Assessment and Reduction Project
CDOM	Colored Dissolved Organic Matter
CE-QUAL-ICM	CE-QUAL Integrated Compartment Model
CMAQ	Community Multiscale Air Quality Modeling System
CSO	Combined Sewer Overflows
CH3D	Curvilinear-Grid Hydrodynamics 3D Model
CTDEEP	Connecticut Department of Energy and Environmental Protection
DELWAQ	Deltares Water Quality Model
DEP	New York City Department of Environmental Protection
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
ECOMSED	Estuarine, Coastal and Ocean Model with Sediment Transport Dynamics
EFDC	Environmental Fluid Dynamics Code
EPA	US Environmental Protection Agency
FVCOM	Finite Volume Community Ocean Model
GUI/DST	Graphical User Interface/Decision Support Tool
HAB	Harmful Algal Bloom
HSPF	Hydrological Simulation Program Fortran
HWQM	Hydrodynamic and Water Quality Models
HWQMS	Hydrodynamic and Water Quality Modeling Support
HYCOM	Hybrid Coordinate Ocean Model
IEC	Interstate Environmental Commission
ISS	Inorganic Suspended Solids
LIS	Long Island Sound
LTCP	Long-Term Control Plan
MGD	Million gallons per day
MEG	Model Evaluation Group
MOCHA	Mid-Atlantic Ocean Climatological and Hydrographic Atlas
MPI	Message Passing Interface
NADP	National Atmospheric Deposition Program

NARR	North American Regional Reanalysis
NJDEP	New Jersey Department of Environmental Protection
NJDOT	New Jersey Department of Transportation
NJHDG	New Jersey Harbor Dischargers Group
NLM	Nutrient Load Models
NOAA	National Oceanic and Atmospheric Administration
NYC	New York City
NYSDEC	New York State Department of Environmental Conservation
PAR	Photosynthetically Available Radiation
POM	Particulate Organic Matter
RCA	Row Column AESOP
RFP	Request for Proposal
RIDEM	Rhode Island Department of Environmental Management
ROMS	Regional Ocean Modeling System
SFM	Sediment Flux Model
SMP	Shared Memory Parallelization
SOD	Sediment Oxygen Demand
SWEM	System-Wide Eutrophication Model
TMDL	Total Maximum Daily Load
TN	Total Nitrogen
TSS	Total Suspended Solids
ugRCA	Unstructured Grid RCA
USACE	US Army Corps of Engineers
USGS	US Geological Survey
WASP8	Water Quality Analysis Simulation Program (Version 8)
WRRF	Wastewater Resource Recovery Facility
WY	Water Year

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1 Background & Introduction

Long Island Sound (LIS) is one of the largest estuaries in the US Environmental Protection Agency (EPA) National Estuary Program, with a watershed drainage area of about 16,000 square miles that includes: most of Connecticut; parts of Massachusetts, New Hampshire and Vermont; a small area of the Connecticut River in Canada; parts of New York City and Westchester County; and north shore areas of Long Island. LIS itself is longer (110 miles) than wider (21 miles), with an average depth of 65 feet and a surface area of 1,300 square miles. Unlike many other estuaries, LIS does not have a major tributary at its upstream end but is tidally connected on both ends, by Block Island Sound on the east and by the East River on the west.

In addition, there are numerous embayments along the Connecticut shoreline (e.g., New Haven Harbor, Niantic Bay) and the north shore of Long Island (e.g., Huntington Bay, Port Jefferson Harbor). The major rivers entering LIS are primarily from Connecticut and include the Housatonic River, Quinnipiac River, Connecticut River, and Thames River. A unique aspect of LIS is the narrow (about 3.5 miles wide) and deep (depths greater than 300 feet) tidal entrance on the east end called “The Race” that exhibits very high tidal currents (upwards of 3-4 knots or 1.5–2.0 meters per second), which is an important feature of the circulation in eastern LIS. On the western end of LIS is the East River, which is another unique feature affecting circulation and nutrient loading due its proximity to NYC and major point sources. Of particular note is the direction of net water flux in the East River, which is comprised of completely mixed, unidirectional (western end) and vertically stratified, two-layered (eastern end) areas with an estimated net water flux direction from LIS to the NY/NJ Harbor (Blumberg & Pritchard, 1997).

1.1 LIS SWEM Review

The University of Connecticut performed a detailed independent evaluation of the prior System-Wide Eutrophication Model (SWEM) development (O’Donnell et al., 2010, 2014) that identified a number of modeling issues. During the application and calibration of SWEM, the vertical eddy coefficients calculated by the hydrodynamic model (ECOM) were reduced in the water quality model (RCA) to improve model-data comparisons of near-bottom DO levels in western LIS during the summer. It should be noted that this vertical mixing adjustment in the water quality model was presented to and approved by the SWEM Model Evaluation Group (MEG) at the time.

It was noted that recent work on mixing in the coastal ocean and comparison of ECOM results to these recent observations in LIS suggested that the original ECOM vertical mixing values were actually realistic and that the values imposed by the RCA vertical eddy coefficient reduction were much too small. In addition, recent observations in LIS indicated that both algal respiration and production were significantly underestimated in SWEM.

Recommendations from these evaluations included: eliminating vertical mixing adjustment in RCA; use of recent estimates of algal respiration and production; refinement of the model grid to provide finer spatial resolution; and use of open-source models and data sharing standards.

1.2 Proposed LIS Model Updates

The New York City Department of Environmental Protection (DEP) LIS Hydrodynamic and Water Quality Modeling Support (HWQMS) project includes the development of updated and refined hydrodynamic and water quality models (HWQMs) of LIS. The updated HWQMs will provide a framework to integrate water quality management planning and assessments in the future to support Clean Water Act compliance required under the 2000 Dissolved Oxygen (DO) Total Maximum Daily Load (TMDL) (NYSDEC & CTDEP 2000), as well as future nutrient management activities and related evaluations. The models will need to accurately represent tidal transport/circulation and water quality over the entire interconnected system (i.e., New York Bight, New York Harbor, offshore coastal waters) and other areas of the region (e.g., New Jersey tributaries, Newark Bay, Sandy Hook Bay), which are defined here as the LIS study area (Figure 5).

The LIS-HWQMS project includes the development of updated and refined open source hydrodynamic and water quality models of LIS. At a minimum, the project will refine the model grid in LIS and coastal embayments to improve lateral mixing and vertical stratification. The models will be calibrated with data from 1994-1995 and 2003-2010 time periods; validated with data from a 2011-2018 time period and include post-audit testing of the models with data from 2019-2022. In addition to the model updates, a Graphical User Interface/Decision Support Tool (GUI/DST) will be developed to allow DEP and stakeholders to view data, setup and run the models (pre-processing) and view model output (post-processing). The GUI/DST will also give DEP and stakeholders the ability to evaluate nutrient management scenarios and view their effects on LIS water quality. Near the end of the project, technology transfer and training sessions will be conducted to transfer the models and GUI/DST to DEP.

One step in the LIS-HWQMS project is to review hydrodynamic and water quality models that could be used in LIS, along with providing an overview of the model setup process. The remaining sections of this document discuss model selection criteria, model review and evaluation, model selection recommendation and an outline of the model setup process. Attachments 1 and 2 provide hydrodynamic and water quality model Fact Sheets for the models evaluated.

2 Model Selection Criteria

The objective of model selection is to choose a model capable of meeting all of the LIS hydrodynamic and eutrophication modeling objectives as identified in the DEP Request for Proposal (RFP). One of the primary criteria for selection of LIS HWQMs is that the model source codes must be open source (i.e., publicly available, non-proprietary) to provide a transparent modeling process for LIS stakeholders; and provide documentation of model setup and theory in a User's Manual. The other modeling objectives, scope items and needs are noted below.

- RFP, Key Project Objective #1: Create and/or expand upon a three-dimensional hydrodynamic model with sufficient spatial resolution, including coastal embayments and tidal rivers, which represents complex bathymetry accurately and is capable of simulating significant physical characteristics and processes, including open water seasonal stratification, in LIS waters.

- RFP, Key Project Objective #2: Model eutrophication processes to accurately capture dissolved oxygen, phytoplankton, organic carbon, and nutrient distributions in the LIS and to provide accurate parameters to support future ecological assessments and models.
- RFP, Key Project Objective #3: Develop a robust model framework that is capable of linking multiple scale hydrodynamic and water quality models, and is updatable to use new data and to simulate future environmental conditions, such as climate change and sea level rise scenarios.
- RFP, Key Project Objective #4: Establish a model framework that facilitates evaluation of multiple planning and management scenarios on water quality (e.g., the impact of sea level rise, increased water temperature due to climate change, or to estimate the benefits of reduced point or non-point source nitrogen loads).
- RFP, Key Project Objective #5: Incorporate open-source coding standards and interoperable data exchange standards to ensure broader access and ability to contribute to hydrodynamic and water quality models testing and development.
- RFP Scope Item #13: Discuss hardware design specifications and configuration requirements for data storage, model execution and data processing. The modeling system should support modern processing technology, including use of parallel and multi-core processors and GPUs.
- RFP listed future need: DEP Integrated Modeling Framework (i.e., ability of models to support living resources and ecological processes).

The next sections provide additional selection criteria and attributes for the HWQMs.

2.1 Hydrodynamic Model

The hydrodynamic model selected for application in LIS must include the following attributes: time-variable and three-dimensional calculations; a horizontal model grid with sufficient spatial resolution to represent shoreline features; vertical model segmentation to represent stratification processes; river, runoff and point source freshwater inflows; tidal and wind forcing; dynamic turbulence-closure schemes; density-driven circulation; atmospheric coupling for surface mixing and heat exchange; and bottom roughness for friction-induced turbulent mixing. The model must provide accurate tidal circulation information to the water quality model to appropriately reflect the transport of salt, heat, suspended solids, nutrients, and phytoplankton so the hydrodynamic and water quality models can reproduce observed salinity, temperature, suspended solids, and water quality constituents, including dissolved oxygen concentrations, which are a key concern in LIS. Figure 1 presents the hydrodynamic model processes expected to be included in the LIS hydrodynamic model.

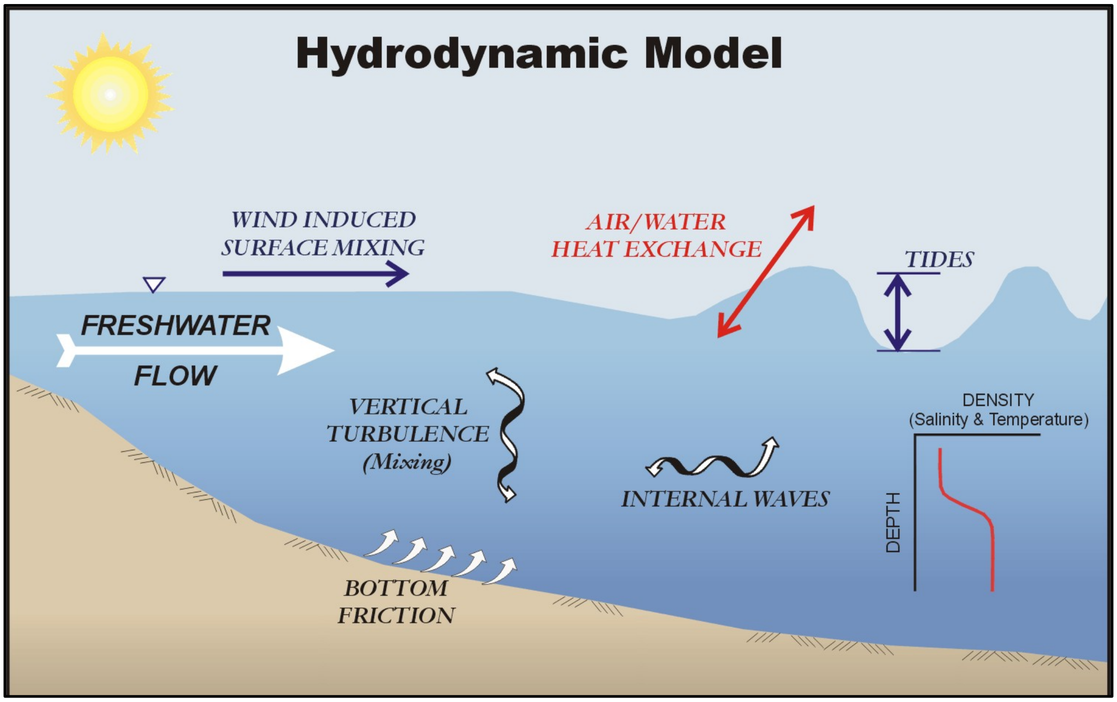

Figure 1. Hydrodynamic Model Key Features

In order to achieve the LIS project objectives, the following key questions need to be addressed by the hydrodynamic model.

- What are the key hydrodynamic (circulation), salinity and temperature characteristics and conditions that need to be modeled?
- What are the spatial scales to be modeled?
- Does the model have a sufficient history of similar applications?
- Is the model supported and does it have a user community?
- Is the model in the public domain or have an open source code with required model documentation of model setup and theory (i.e., User's Manual)?
- Are there previous efforts with an appropriate model that can be used?
- Is the model capable of meeting all of the identified LIS RFP project objectives?

2.2 Water Quality Model

The water quality (eutrophication) model selected for application in LIS must include the following attributes: time-variable and three-dimensional calculations using the same model grid as the hydrodynamic model; particulate and dissolved organic nitrogen, phosphorus and carbon including, at a minimum, labile and refractory fractions; inorganic nitrogen (ammonia and nitrite plus nitrate); dissolved inorganic phosphorus (ortho-phosphate); biogenic and available silica; multiple algal groups; dissolved oxygen; inorganic suspended solids; light attenuation; particulate organic matter settling; and a coupled sediment flux model (SFM). Figure 2 presents the eutrophication model kinetics expected to be included in the LIS eutrophication model.

Brief descriptions of the SFM framework and processes that affect sediment nutrient fluxes and sediment oxygen demand (SOD) are presented below. A more detailed discussion of the SFM development is found in Sediment Flux Modeling (DiToro, 2001). The general interactions occurring in the sediment are shown in the sediment model schematic presented in Figure 3. SFM is formulated with two compartments, an aerobic and anaerobic sediment layer, and uses the settling fluxes from the eutrophication model as inputs.

Particulate organic matter (POM), detrital or algal nitrogen, phosphorus, silica and carbon, settles through the water column and is deposited to the sediment. This settling of POM is the driving force behind the various decay mechanisms occurring in the sediment. The POM that settles into the sediment is classified into three reactivity classes referenced as G1, G2 and G3. The G1 component is the most reactive with a half-life of about 20 days. The G2 component has a half-life of about one year, and the G3 component is basically non-reactive.

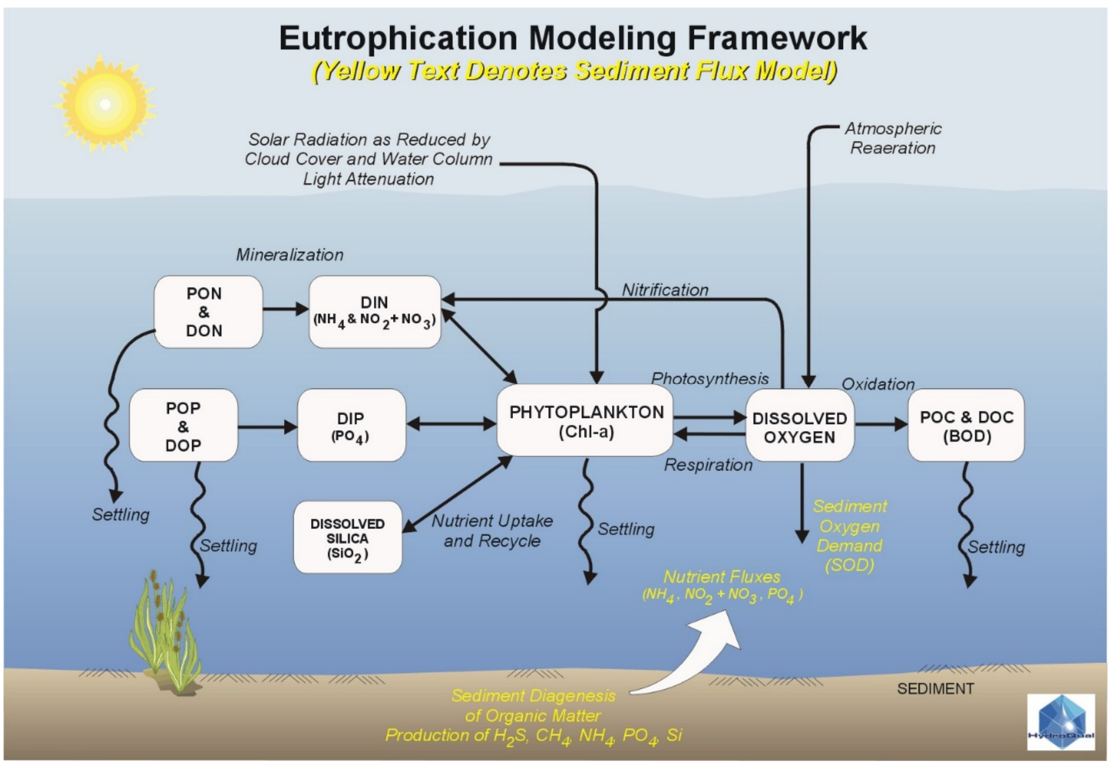

Figure 2. Eutrophication Model Kinetics

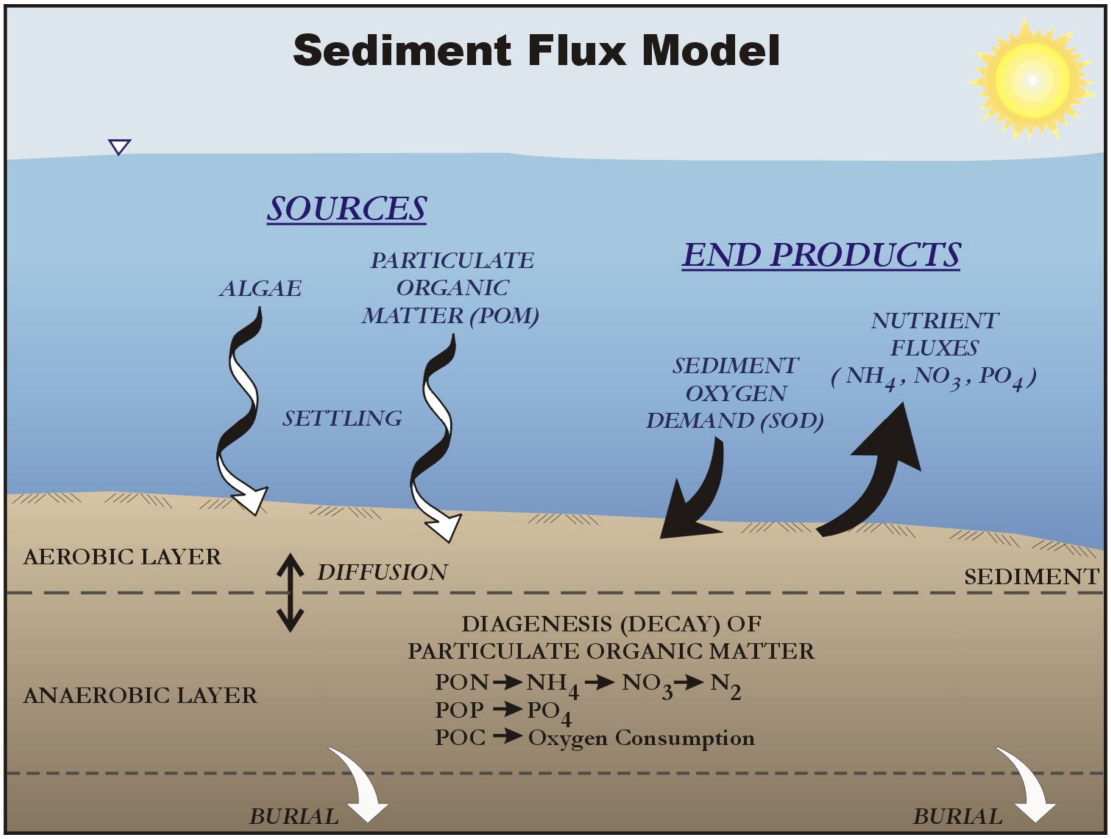

Figure 3. Sediment Flux Model Key Processes

Once POM settles to the sediment, it can either decompose through diagenesis to the various inorganic end products of nitrogen, phosphorus, carbon and silica or become buried in the sediments. The particulate organic nitrogen, phosphorus and silica that settle to the sediment eventually decompose following various temperature-dependent kinetic pathways into their associated inorganic forms: ammonia, nitrate, orthophosphate, and available silica. Depending upon overlying water DO concentrations and the water column/sediment dissolved concentration gradients, ammonia, nitrate, orthophosphate and available silica can either flux out of or into the sediments.

The temperature-dependent decomposition of particulate organic carbon in the sediment results in the formation of sulfide. Depending upon the overlying water column DO concentration, the sulfide is either oxidized in the sediment (SOD) or fluxed into the water column at low dissolved oxygen levels as oxygen-demanding equivalents or aqueous SOD (O2EQ). In addition to the carbon component of the SOD, the nitrification of ammonia to nitrate consumes oxygen and, therefore, is also included in the calculation of the total SOD.

This simplified description of the sediment flux model should not detract from the importance of biogeochemical processes in the sediment bed in the context of an estuarine system like LIS. The nutrient fluxes into the water column can be a significant source of nutrients needed for algal growth and a significant source of deoxygenation potential via SOD. Also, the delivery and storage capacity of POM in the sediments during higher flow and cooler seasons (fall, winter, spring) plays a vital role in the cycling of nutrients back into the water column and exertion of SOD during the warmer spring and summer months. The use of the sediment flux model completes the mass balance between the sediment and the water column mechanistically, rather than having to estimate and assign nutrient fluxes as model inputs. In general, the inclusion of the sediment flux model in the modeling framework greatly improves the scientific credibility and the ability to predict water quality dynamics over long time periods on the order of a decade or more.

In order to achieve the LIS project objectives, the following key questions need to be addressed by the water quality model.

- Does the model have a sufficient history of similar applications?
- Is the model supported and does it have a user community?
- Is the model in the public domain or have an open source code with required model documentation of model setup and theory (i.e., User's Manual)?
- Are there previous efforts with an appropriate model that can be used?
- Does the model run simultaneously with the hydrodynamic model or can the water quality model be run separately from the hydrodynamic model?
- Is the model capable of representing complex DO dynamics and have multiple phytoplankton groups?
- Does the model either have a coupled or built-in SFM?
- Is the model capable of meeting all of the identified LIS RFP project objectives?

3 Model Review & Evaluation

One overall hydrodynamic and water quality model criterion that will guide model selection is that the hydrodynamic and water quality models are already capable of communicating with one another, as further code development to build this linkage is not included in the project.

3.1 Hydrodynamic Models

This section provides a discussion of the required model selection criteria, attributes and reviews the most appropriate candidate hydrodynamic models for application in LIS. In addition, model Fact Sheets were developed that present background capabilities and information for the nine candidate hydrodynamic models reviewed herein. These Fact Sheets are included in Attachment 1.

As most hydrodynamic models simulate the required general circulation characteristics, it is important to identify the key aspects that are important to LIS; and to choose a hydrodynamic model that will address these key aspects. For the LIS modeling, the following key attributes have been identified.

- Full three-dimensional (3D) and time-variable (dynamic) momentum, continuity, density, salinity and temperature formulations. While most complex hydrodynamic models presently have these full capabilities, these components are important to list as attributes for the hydrodynamic model.

- Ability to accurately represent tidal circulation in estuarine and coastal systems.

- Flexible model grid and sub-grid modeling. That is, the ability to have different grid sizes to allow more detail in areas of interest, with a curvilinear orthogonal or flexible mesh, coastline-conforming coordinate system (horizontal) and with either a sigma, z-level or combined vertical segmentation capability to accurately represent bathymetry in the study area.

- Accurate simulation of wind-driven circulation. Due to the open nature of LIS, wind-driven circulation plays an important role in the overall water circulation.

- Full atmospheric heat exchange. This will include the important interactions between the atmosphere and water (heating/cooling) as driven by short- and long-wave solar radiation, conductive heating/cooling, evaporative cooling and vertical extinction of surface solar radiation in the water column.

The hydrodynamic model should also have a relatively long history of similar applications, regulatory acceptance and have a user base so that potential errors or coding issues have been fully vetted and tested through the user community. This allows for ongoing model maintenance and updates in the future.

As required by DEP, a public domain hydrodynamic model is needed that should also have an open source code (available to the public) and User's Manual so that the "black box" element of how important calculations are completed is readily available for review. This attribute helps the modeler better understand underlying assumptions and limitations of the hydrodynamic model. Advantages of a public-domain model, in addition to having open source code, are that it makes it easier to implement code enhancements if needed for the project and that users are not required to purchase the model along with the associated annual maintenance costs.

Based on our understanding of the important hydrodynamic processes that need to be accurately modeled and DEP needs, we have identified nine peer-reviewed, public-domain models for review. MIKE3D FM was considered but eliminated because it is a proprietary model. The nine candidate hydrodynamic models are noted below.

- Estuarine, Coastal and Ocean Model with Sediment Transport Dynamics (ECOMSED)
- Finite Volume Community Ocean Model (FVCOM)
- Environmental Fluid Dynamics Code (EFDC) – three versions evaluated
  - EFDCepa – EPA version
  - EFDC+ – DSI, LLC version
  - SNL-EFDC – Sandia National Laboratories version

- Regional Ocean Modeling System (ROMS)
- Curvilinear-Grid Hydrodynamics 3D Model (CH3D)
- Delft3D-Flow
- Adaptive Hydraulics Model (AdH)

A hydrodynamic model-selection matrix was developed to assist in selecting an appropriate model for application to the LIS. Descriptions of the model selection criteria and model attributes are presented below and in Table 1 and Table 2 for the nine hydrodynamic models identified.

Selection Criteria

- Vertical Segmentation – This criterion is included to represent RFP Key Project Objective #1 (create and/or expand upon a three-dimensional hydrodynamic model) with three options included for ranking (sigma, sigma/S or sigma/Z, sigma/S/sigma-Z).

- Horizontal Segmentation – This criterion is included to represent RFP Key Project Objective #1 (create and/or expand upon a three-dimensional hydrodynamic model) with three options included for ranking (orthogonal, curvilinear orthogonal, flexible mesh).

- Vertical Turbulence Closure – This criterion is included to represent RFP Key Project Objective #1 (create and/or expand upon a three-dimensional hydrodynamic model) with three calculation options included for ranking (no option, 1 method, more than 1 method).

- Parallelization Method – This criterion is included to represent RFP Scope Item #13 (modeling system should support modern processing technology) with three options included for ranking (no parallelization, shared memory parallelization (SMP), message passing interface (MPI)).

- Nesting Method – This criterion is included to represent RFP Key Project Objective #3 (model framework capable of linking multiple scale hydrodynamic and water quality models) with three options included for ranking (no nesting, 1-way nesting, 2-way nesting).

- Public-Domain Source Code – This criterion is included to represent RFP Key Project Objective #5 (incorporate open-source coding standards and interoperable data exchange standards) with three options included for ranking (not available, available with restrictions, fully available).

- Data Exchange – This criterion is included to represent RFP Key Project Objective #5 (incorporate open-source coding standards and interoperable data exchange standards) with three options included for ranking (no capability but can be added, has capability but further coding needed, has capability).

- Coupled Water Quality Model Applications – This criterion, although a bit subjective, is included to provide some measure for the number of linked water quality model applications to minimize the risk of finding errors during application with three options included for ranking (<5 applications, 5-25 applications, >25 applications).

Attributes

- Number of Spatial Dimensions – one, two or three.
- Dynamic – ability to allow time-variable model input, calculations and output, as opposed to steady-state (constant in time).
- Structures – ability to represent structures with a "thin wall" approach between model segments to better represent narrow barriers, which minimizes the need to resolve structures with model segments, thereby allowing better control over model resolution.
- Tidal Environment – capable of accurately representing tidal circulation.
- Full Heat Balance – capable of accurately representing atmospheric heating and cooling dynamics as opposed to treating temperature as a conservative parameter.
- Spatial Meteorology – capable of representing different meteorological inputs on a spatially varying basis.
- Wave Model Available – has a coupled wave model available for future use outside of this project.
- Sediment Transport Model Available – has a sediment transport model available for future use outside of this project. In this context, a sediment transport model is defined as a model that calculates the movement (settling and resuspension) of cohesive and non-cohesive sediments to/from the sediment bed.

The model selection criteria were established to reflect the RFP Key Objectives and Scope Items to provide an objective process for selecting a hydrodynamic model for LIS. Based on the important selection criterion of using a public-domain model, the EFDCepa and EFDC+ hydrodynamic models are not suitable for use in the LIS modeling project. The CH3D hydrodynamic model (all advanced features) is not in the public domain (i.e., model source code is not freely available), but it should be noted that the base CH3D model code is publicly available and, therefore, is considered to be in the public domain.

Using the model selection criteria presented in Table 1, the hydrodynamic models were ranked by assigning a value of 1 for a low ranking, 2 for a medium ranking and 3 for a high ranking. As noted, EFDCepa and EFDC+ were not ranked because the model codes are not in the public domain. Based on this ranking process the following top 3 model selection order resulted.

1. FVCOM, ROMS and Delft3D (score of 20)
2. AdH (score of 18)
3. ECOM and CH3D (score of 17)

Table 1. Hydrodynamic Models – Rating Criteria

Criterion	ECOMSED	FVCOM	EFDCepa / EFDC+	SNL-EFDC	ROMS	CH3D	Delft3D	AdH
Vertical Segmentation[1]	Low	High	Low / High	Low	Medium	Medium	Medium	Medium
Horizontal Segmentation[1]	Medium	High	Medium / Medium	Medium	Medium	Medium	High	High
Vertical Turbulence Closure[1]	Medium	High	Medium / Medium	Medium	High	High	High	High
Parallelization Method[13]	Medium	High	High / High	High	High	High	High	High
Nesting Method[3]	Medium	Medium	Medium / Medium	Medium	High	Medium	Medium	Medium
Public Domain Source Code[5]	High	Medium	Low* / Low*	High	High	Medium	High	High
Data Exchange (e.g., NetCDF)[5]	Medium	High	Low / High	Low	High	Low	High	Low
Coupled WQ Model Applications	High	Low	High / High	Low	Low	Medium	Low	Low

Notes:
Vertical Segmentation: low (1 option, sigma), medium (2 options, sigma/S or sigma/Z), high (3 options, sigma/S/sigma-Z)
Horizontal Segmentation: low (orthogonal), medium (curvilinear orthogonal), high (flexible mesh)
Vertical Turbulence Closure: low (none), medium (1 option, Mellor-Yamada), high (more than 1 option)
Parallelization Method: low (none), medium (SMP), high (MPI)
Nesting Method: low (none), medium (1-way), high (2-way)
Public Domain Source Code: low (no), medium (yes w/ restrictions), high (yes)
Data Exchange: low (no capability but can be added), medium (has capability but further coding needed), high (already has capability)
Coupled Water Quality Model Applications: low (<5), medium (5-25), high (>25)
* - Does not meet RFP Key Objective #5

1 – RFP, Key Project Objective #1: Create and/or expand upon a three-dimensional hydrodynamic model with sufficient spatial resolution, including coastal embayments and tidal rivers, which represents complex bathymetry accurately and is capable of simulating significant physical characteristics and processes, including open water seasonal stratification, in LIS waters.
3 – RFP, Key Project Objective #3: Develop a robust model framework that is capable of linking multiple scale hydrodynamic and water quality models, and is updatable to use new data and to simulate future environmental conditions, such as climate change and sea level rise scenarios.
5 – RFP, Key Project Objective #5: Incorporate open-source coding standards and interoperable data exchange standards to ensure broader access and ability to contribute to hydrodynamic and water quality models testing and development.
13 – RFP Scope Item #13: Discuss hardware design specifications and configuration requirements for data storage, model execution and data processing. The modeling system should support modern processing technology, including use of parallel and multi-core processors and GPUs.

Table 2. Hydrodynamic Models – Attributes

Attribute	ECOMSED	FVCOM	EFDCepa / EFDC+	SNL-EFDC	ROMS	CH3D	Delft3D	AdH
Number of Dimensions	23D	23D	123D	123D	23D	3D	123D	123D
Dynamic	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Structures	Thin Wall	Groyne/Dike	Thin Wall	Thin Wall	No	Thin Wall	Thin Wall	Thin Wall
Tidal Environment	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Full Heat Balance[a]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Spatial Meteorology	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Wave Model Available	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sediment Transport Model Available	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note:
a – Including the capability to represent spatial and temporal variability in light extinction coefficients.

3.2 Water Quality Models

This section provides a discussion on the required model selection criteria, attributes and reviews the most appropriate candidate water quality models for model application in LIS. In addition, model Fact Sheets were developed that present background capabilities and information for the ten water quality models reviewed in this section. These Fact Sheets are presented in Attachment 2.

As most of the identified water quality models simulate the required general characteristics, it is important to identify the key aspects that are important to LIS and to choose a water quality model that will address these key aspects. For the LIS modeling, the following key attributes have been identified.

- Three-dimensional (3D) and time-variable (dynamic).
- Flexible model grid and sub-grid modeling – ability to run on the same or aggregated grid used by the hydrodynamic model.
- Eutrophication kinetics – phytoplankton, nutrients, carbon oxidation, DO.
- Multiple phytoplankton groups – winter diatoms, spring/summer/fall assemblages as needed.
- Coupled sediment flux model.

As was the case for the hydrodynamic model, the water quality model should also have a relatively long history of similar applications, regulatory acceptance and have a user base so that potential errors or coding issues have been fully vetted and tested through a user community. This allows for ongoing model maintenance and updates in the future.

As required by DEP, a public-domain water quality model is needed that should also have an open source code (available to the public) and User's Manual so that the "black box" element of how important calculations are completed is readily available for review. This attribute helps the modeler better understand underlying assumptions and limitations of the water quality model. Advantages of a public-domain model, in addition to having open source code, are that it makes it easier to implement code enhancements if needed for the project and that users are not required to purchase the model along with the associated annual maintenance costs.

Based on our understanding of the important water quality processes that need to be accurately modeled in order to simulate nutrients, carbon, phytoplankton and DO in LIS, we have identified ten peer-reviewed, public-domain models for review. These models are all process-based, dynamic, are applicable to estuaries and coastal systems, and are non-proprietary. Also, all of the water quality models can be coupled with at least one of the identified hydrodynamic models. DHI's MIKE ECO Lab model was considered but eliminated because it is proprietary. The ten candidate water quality models are noted below.

- Row Column AESOP (RCA)

- Unstructured Grid RCA (ugRCA)
- AQUATOX
- A2EM
- Environmental Fluid Dynamics Code (EFDC) – three versions evaluated
  - EFDCepa – EPA version
  - EFDC+ – DSI, LLC version
  - SNL-EFDC
- Water Quality Analysis Simulation Program version 8 (WASP8)
- CE-QUAL-ICM
- DELWAQ

A water quality model selection matrix was developed to assist in selecting an appropriate model for application to the LIS. Descriptions of the model selection criteria and model attributes are presented below and in Table 3 and Table 4 for the ten water quality models identified.

Selection Criteria

- Eutrophication Kinetics – This criterion is included to represent RFP Key Project Objective #2 (model eutrophication processes to accurately capture water quality distributions in LIS) with three options included for ranking (nitrogen based algal growth, nitrogen/phosphorus based algal growth, nitrogen/phosphorus/silica based algal growth).

- Multiple Phytoplankton Groups – This criterion is included to represent RFP Key Project Objective #2 (model eutrophication processes to accurately capture water quality distributions in LIS) with three options included for ranking (one group, two groups, more than two groups).

- Labile/Refractory Organic Matter – This criterion is included to represent RFP Key Project Objective #2 (model eutrophication processes to accurately capture water quality distributions in LIS) with three options included for ranking (not included, particulate or dissolved, particulate and dissolved).

- Living Resource Submodels – This criterion is included to represent RFP Key Project Objective #2 (model eutrophication processes to accurately capture water quality distributions in LIS) with three options included for ranking (not included, SAV only, SAV and filter feeders).

- Sediment Flux Model – This criterion is included to represent RFP Key Project Objective #4 (model framework that facilitates evaluation of multiple planning and management scenarios on water quality) with three options included for ranking (not included, intermediate, detailed).

- Parallelization Method – This criterion is included to represent RFP Scope Item #13 (modeling system should support modern processing technology) with three options included for ranking (no parallelization, SMP, MPI).

- Public Domain Source Code – This criterion is included to represent RFP Key Project Objective #5 (incorporate open-source coding standards and interoperable data exchange standards) with three options included for ranking (not available, available with restrictions, fully available).

- Data Exchange – This criterion is included to represent RFP Key Project Objective #5 (incorporate open-source coding standards and interoperable data exchange standards) with three options included for ranking (no capability but can be added, has capability but further coding needed, has capability).

- Coupled Hydrodynamic Model Applications – This criterion, although a bit subjective, is included to provide some measure for the number of linked hydrodynamic model applications to minimize the risk of finding errors during application with three options included for ranking (<5 applications, 5-25 applications, >25 applications).

Attributes

- Light Extinction Formulation – has the ability to calculate light extinction as a function of suspended solids, chlorophyll-a, DOC and/or detrital POM; and can assign spatially and temporally variable light extinction model inputs.

- Algal Light Formulation – has the ability to use different algal light formulations (e.g., photo-inhibition, saturating).

- Reaeration Formulation – has the ability to calculate reaeration as a function of wind and surface water currents.

- Algal Nutrient Stoichiometry – has the ability to use variable algal nutrient stoichiometry.

- Algal Formulation – has the ability to use standard algal growth kinetics and/or Laws-Chalup based algal growth kinetics.

- Mass Balance Output – has the ability provide mass-balance output at various interfaces (e.g., vertical transect, boundary).

- Hydrodynamic Model Coupling Method – water quality model reads a saved hydrodynamic transport file (i.e., external coupling) or executes together with the hydrodynamic model (i.e., internal coupling).

The model selection criteria were established to reflect the RFP Key Objectives and Scope Items to provide an objective process for selecting a water quality model for LIS. Based on the important selection criterion of using a public-domain model, the EFDCepa, EFDC+ and WASP8 water quality models are not suitable for use in the LIS modeling project. It should be noted that the WASP8 source code is not available to the general public but may be available to model developers.

AQUATOX was originally developed to model organic toxicants in aquatic food chains, but has been modified in recent decades for eutrophication applications such as nutrient criteria evaluations and TMDLs. While AQUATOX has been used with EFDC hydrodynamics, it is generally used with relatively simple model segmentation. Although multiple segments can be simulated, the physical and hydrodynamic complexities of LIS would require unrealistically cumbersome external development of inputs for the many segments that would be needed. Thus, AQUATOX is not being considered as a reasonable option.

Using the model selection criteria presented in Table 3, the water quality models were ranked by assigning a value of 1 for a low ranking, 2 for a medium ranking and 3 for a high ranking. As noted, EFDCepa, EFDC+ and WASP8 were not ranked because the model codes are not in the public domain. Based on this ranking process the following top 3 model selection order resulted.

1. RCA (score of 25)
2. CE-QUAL-ICM (score of 23)
3. ugRCA and DELWAQ (score of 22)

Based on the top hydrodynamic models from the selection process (FVCOM, ROMS, Delft3D), the water quality models that can be linked to these three hydrodynamic models include ugRCA, RCA, CE-QUAL-ICM and DELWAQ.

Table 3. Water Quality Models – Rating Criteria

Criterion	RCA	ugRCA	AQUATOX	A2EM	EFDCepa / EFDC+	SNL-EFDC	WASP8	CEQUAL-ICM	DELWAQ
Eutrophication Kinetics[2]	High	High	High	High	High / High	High	High	High	High
Multiple Phyto Groups[2]	High	High	High	High	High / High	High	High	High	High
Labile/Refractory Organic Matter[2]	High	High	High	High	Medium / Medium	Medium	Medium	Medium	Medium
Living Resource Submodels[2,*]	High	Low	High	High	Medium / High	Medium	Medium	High	Low
Sediment Flux Model[4]	High	High	High	High	High / High	High	High	High	High
Parallelization Method[13]	Medium	High	Low	Medium	High / High	High	Low	Medium	High
Public Domain Source Code[5]	High	Medium	High	Low	Low* / Low*	High	Low*	High	High
Data Exchange (e.g., NetCDF)[5]	Medium	High	Low	Low	Low / High	Low	Low	Medium	High
Coupled Hydro Model Applications	High	Low	Low	Low	High / High	Low	High	Medium	Low

Notes:
Eutrophication Kinetics: low (N only), medium (N/P only), high (N/P/Si)
Multiple Phytoplankton Groups: low (1), medium (2), high (>2)
Labile/Refractory OM: low (none), medium (particulate or dissolved), high (particulate and dissolved)
Living Resource Submodels: low (none), medium (SAV), high (SAV/filter feeders)
Sediment Flux Model: low (none), medium (intermediate), high (detailed)
Parallelization Method: low (none), medium (SMP), high (MPI)
Public Domain Source Code: low (no), medium (yes w/ restrictions), high (yes)
Data Exchange: low (no easy capability), medium (has capability but addition part of scope), high (already has capability)
Coupled Hydrodynamic Model Application: low (<5), medium (5-25), high (>25)

2 – RFP, Key Project Objective #2: Model eutrophication processes to accurately capture dissolved oxygen, phytoplankton, organic carbon, and nutrient distributions in the LIS and to provide accurate parameters to support future ecological assessments and models.

4 – RFP, Key Project Objective #4: Establish a model framework that facilitates evaluation of multiple planning and management scenarios on water quality (e.g., the impact of sea level rise, increased water temperature due to climate change, or to estimate the benefits of reduced point or non-point source nitrogen loads).

5 – RFP, Key Project Objective #5: Incorporate open source coding standards and interoperable data exchange standards to ensure broader access and ability to contribute to hydrodynamic and water quality models testing and development.

13 – RFP Scope Item #13: Discuss hardware design specifications and configuration requirements for data storage, model execution and data processing. The modeling system should support modern processing technology, including use of parallel and multi-core processors and GPUs.

* – DEP Integrated Modeling Framework future need (i.e., living resources and ecological processes).

Table 4. Water Quality Models – Attributes

Attribute	RCA	ugRCA	AQUATOX	A2EM	EFDCepa / EFDC+	SNL-EFDC	WASP8	CEQUAL-ICM	DELWAQ
Light Extinction Formulation	Yes	Yes	Yes	Yes	Yes / Yes	Yes	Yes	Yes	Yes
Algal Light Formulation	Yes	Yes	No	No	Yes / Yes	Yes	No	No	No
Reaeration Formulation	Yes	Yes	Yes	Yes	Yes / Yes	Yes	Yes	Yes	Yes
Algal Nutrient Stoichiometry	Yes	Yes	Yes	Yes	Yes / Yes	Yes	No	Yes	No
Algal Formulation	Yes	Yes	Yes	No	No / No	No	No	No	No
Mass Balance Output	Yes	Yes	Yes	No	Yes / Yes	Yes	No	Yes	Yes
Hydro Coupling Method	External	External	External	External	External / Internal	Internal	External	External	External

4 Other Model Selection Factors

Many of the hydrodynamic and water quality models have very similar capabilities and model data needs and would be applicable for LIS modeling. The recommendations for LIS HWQMs are ultimately based on the models having the requisite features for modeling LIS and meeting the established RFP Key Objectives and Scope Items, as noted above. In addition to the selection criteria presented in Tables 1 and 3, other subjective criteria are worth noting so that they can also be considered in the model selection process. These subjective criteria are discussed further below.

- The developers' familiarity with the selected models can minimize upfront learning of new models, provide increased model development efficiency (i.e., tools exist for setting up model inputs and processing model output) and maximizes ability to meet project deadlines.
- Local familiarity and use in regulatory applications of the selected models by regional State and Federal agencies can provide easier acceptance of the models for application in LIS and use of the resulting management scenario results in the decision-making process.

HDR is very familiar with the use of ECOMSED and RCA. ECOMSED and RCA have been applied locally on a number of regulatory-driven water quality projects in Connecticut, New York and New Jersey. These projects include decades of model application in LIS as part of LIS nutrient and DO TMDL studies that required use of the ECOMSED hydrodynamic model to calculate tidal circulation in LIS and the coupled RCA eutrophication model for use in the water quality modeling. The ECOMSED and RCA models were also used to aid in developing a nutrient-trading program in Connecticut to allow more economical point-source nutrient reductions. In addition, the ECOMSED and RCA models have been applied throughout NYC water bodies (i.e., Hudson River, East River, western LIS, Jamaica Bay, New York Harbor) as part of DEP LTCP development and for other watershed management activities.

Beyond local applications of ECOMSED and RCA, these models have been used in numerous estuarine and lacustrine systems around the country for nutrient-management and DO-impact evaluations with State and Federal agencies. ECOMSED has been applied separately (thermal studies) or coupled with RCA (water quality studies) in the following water bodies: Forge River TMDL (NY), Port Jefferson Harbor (NY), Great Bay Estuary (NH), Massachusetts Bay (MA), James River (VA), Delaware River (NJ/PA/DE), Tar-Pamlico Estuary (NC), Tampa Bay (FL), Fenholloway River/Gulf of Mexico (FL), St. Andrews Bay (FL), Escambia/Pensacola Bay (FL), Perdido Bay (FL), San Joaquin River/Stockton Deep Water Ship Channel (CA), Newport Bay (CA), Upper Mississippi River/Lake Pepin (MN), and Milwaukee Harbor/Lake Michigan (WI). In addition, ECOMSED and RCA are currently being used as part of Superfund RI/FS sediment-transport and contaminant modeling in the tidal Passaic River and Newark Bay; Newtown Creek Superfund sediment transport and contaminant modeling; and also for the prior Hudson River Foundation and current NJDOT Contaminant Assessment and Reduction Project (CARP) contaminant modeling in NY/NJ Harbor. Attachment 3 contains a list of other coupled ECOMSED and RCA model applications completed by HDR around the country that have been used in regulatory settings.

Based on the results of the hydrodynamic and water quality model selection criteria, one set of models that ranked the highest was the ROMS hydrodynamic model and the RCA water quality model. Both of these models have been well tested and applied around the country, with ROMS providing a more formal user group and RCA being more familiar for site-specific adaptation by HDR to support LIS modeling needs. There have been a number of recent ROMS-RCA coupled water quality applications that make this combination of models intriguing. ROMS-RCA was recently applied to the tidal Chester River (Testa et al., 2015) and in Chesapeake Bay for harmful algal bloom (HAB) evaluations (Li and Glibert, 2020), for a model comparison study (Irby et al., 2013), and an acidification study in Chesapeake Bay (Shen et al., 2019).

After a recent discussion with the Chester River ROMS-RCA modelers (Damian Brady – University of Maine, Jeremy Testa – University of Maryland and Yun Li – University of Delaware), HDR believes that this combination of hydrodynamic and water quality models provides a sound set of modeling tools that meets the RFP Key Objectives and Scope Items. This includes the potential for MPI parallelization in the RCA water quality model.

5 Model Setup Process

This section describes the model setup process for the hydrodynamic and water quality models based on our experience in LIS and other similar waterbodies. HDR's previous experience modeling LIS serves as the basis for setup of the new LIS models. Since modeling is an iterative process, the final model setup may deviate from the starting point as the project progresses. This document serves as the rationale for the initial model setup process.

It is understood that there may be deviations in input requirements between the different hydrodynamic and water quality models, so this Model Setup Process section will address the inputs that are generally required. HDR's preferred approach to modeling is to start with the basic functionality of a model and then add complexity as warranted and supported by available data.

The LIS model setup will be completed for four modeling time periods as follows.

- The SWEM calibration time period of October 1, 1994 through September 30, 1995 (water year (WY) 1995) will be used for initial model calibration using the refined and updated LIS HWQMs.
- Data from calendar years 2003 through 2010 will be used for further calibration of the LIS HWQMs.
- Data from calendar years 2011 through 2018 will be used for validation of the LIS HWQMs.
- Data from calendar years 2019 through 2022 will be used for post-auditing of the LIS HWQMs.

For WY 1995, the intent will be to use as many of the previously developed SWEM model inputs as possible to allow a comparison of the model results between past SWEM modeling and the new LIS modeling using the refined model grid. As required, additional model calibration will be completed to WY 1995 data to improve model-data comparisons (particularly for DO) before proceeding to the other modeling time periods. Model skill assessment using the criteria outlined in the QAPP will be completed to assess how well the original model calibration and updated model calibration compare with the data.

There are two potential outcomes from application of the new LIS models to the WY 1995 data and comparisons to past SWEM model results. It should be noted that application of the new LIS models will not use the vertical mixing reduction assigned in the past SWEM water quality model (RCA). The potential outcomes are noted below.

1. The new LIS models using the refined spatial model grid (i.e., finer (more) lateral model segments and embayment segmentation) and 10 vertical layers produce acceptable model-data comparisons for water elevation, salinity and temperature with the hydrodynamic model; and produce acceptable model-data comparisons for particulate/dissolved organic matter (C/N/P), inorganic nutrients, chlorophyll-a and dissolved oxygen with the water quality model. If this result occurs, the LIS modeling would move onto the long-term model calibration (2003-2010) and validation (2011-2018) time periods.

2. The new LIS models using the refined spatial model grid (i.e., finer (more) lateral model segments and embayment segmentation) and 10 vertical layers do not produce acceptable model-data comparisons with either the hydrodynamic model or the water quality model or both. If this result occurs, further model updates would be pursued to produce acceptable model-data comparisons. These further updates may include: use of more vertical layers; use of different vertical closure routines; use of different vertical segmentation; updated algal production and respiration rates; updated carbon oxidation rates; revised labile/refractory splits for external loads; and further SFM rate adjustments. Once acceptable model-data comparisons are achieved then the LIS modeling would move onto the long-term model calibration (2003-2010) and validation (2011-2018) time periods.

It should be noted that acceptable model-data comparisons are defined and are presented in the approved LIS QAPP in Section 1.7.2 (Model Output Criteria).

This new LIS model development process for the WY 1995 data and comparisons to past SWEM model results is summarized in the flow chart presented in Figure 4.

The modeling will also include two embayment models, one in Connecticut and one on the north shore of Long Island, that have not been selected yet. The approach to modeling the embayments will be similar to the approach used for the open water LIS modeling. One exception may be the assignment of offshore boundary conditions that will either be based on available data or based on output from the open waters LIS model during development and calibration steps. Ultimately, use of the open waters LIS model to define embayment model boundary conditions will be dependent on scheduling of the embayment modeling task. When applying the embayment models for management scenarios, the open waters LIS model will be used to assign offshore boundary conditions to couple regional

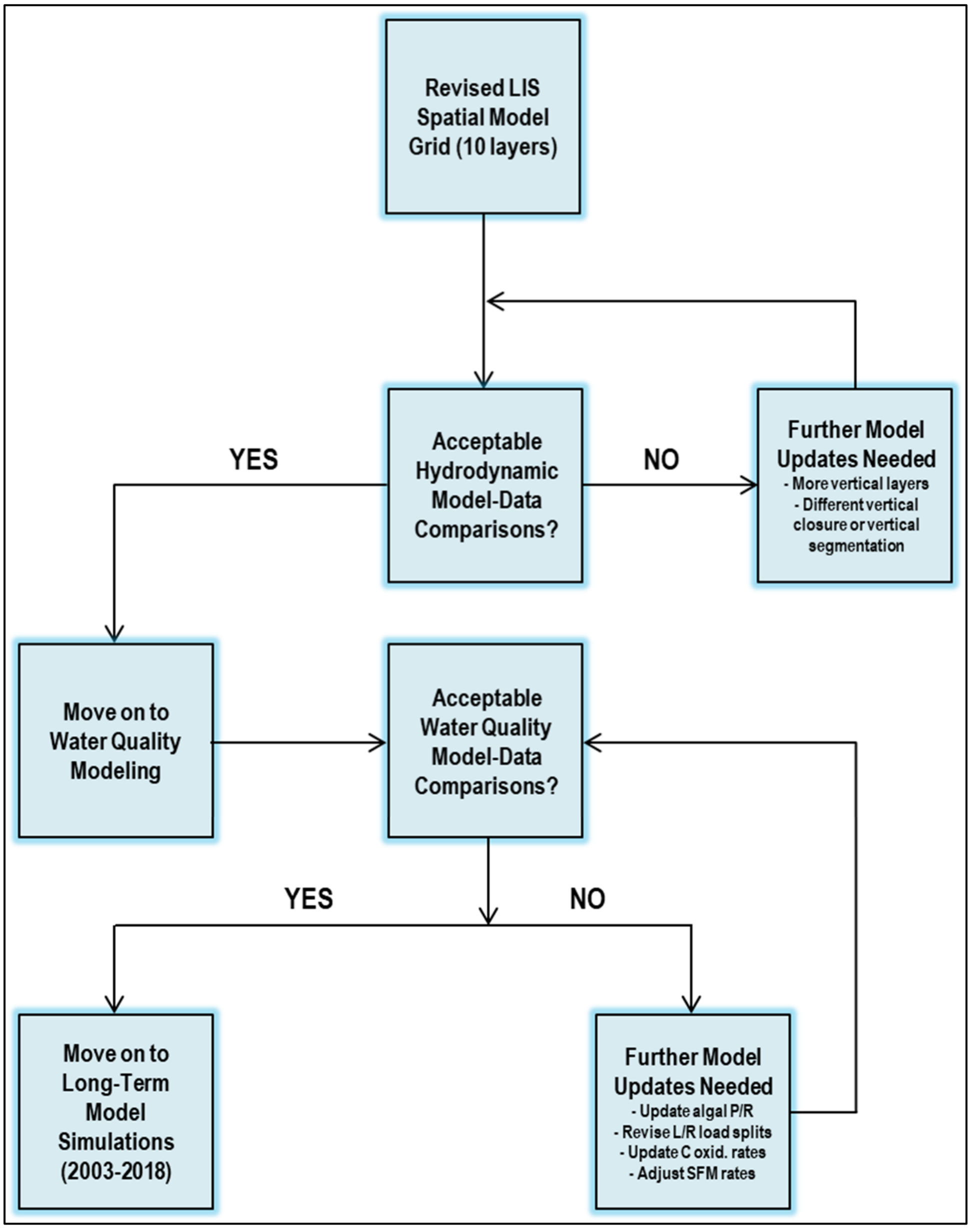

Figure 4. WY 1995 LIS Model Development Process

management scenarios with embayment specific scenarios. Additionally, loading sources that are considered negligible in the open waters LIS model may be considered for inclusion in the embayment models due to local importance.

The selection of the embayment model offshore boundary condition location is an important consideration in developing these model grids. That is, internal model calculations and loading sources should have minimal impact at the boundary condition locations. During embayment model grid development, preliminary model runs will be completed to test whether the offshore model boundary condition location is sufficiently removed from the areas of interest. The boundary condition location may also be evaluated using the open waters LIS model that will include embayment areas. This can be accomplished by assigning a tracer to embayment model freshwater inputs and/or point sources and evaluating the tracer concentrations at the model boundary condition locations.

5.1 Hydrodynamic Model

Hydrodynamic model setup includes revising the model grid and developing inputs for open boundary conditions, freshwater inputs (e.g., rivers, point sources) and meteorological inputs. Hydrodynamic model setup also requires a choice as to which version of the code to use as the starting point.

5.1.1 Model Grid

The starting point of the model setup is to define the spatial model domain. Based on previous modeling in LIS, the model domain will cover a similar area to SWEM or the DEP Open Waters LTCP Model, which covers an area from approximately Nantucket Shoals in the north to Cape May in the south and extends to the 100-meter isobath to the east. The model grid presented in Figure 5 is from the DEP Open Waters LTCP Model and the focus of that effort was in NYC area water bodies in the western region of the domain. Although the focus of this effort was in the western region of the model, the model-data salinity/temperature comparisons in the eastern Sound are good even without the calibration focused on this region of the model. This suggests that even the coarse model grid used in the Open Waters LTCP Model grid in the eastern Sound suitably resolved water fluxes through the Race. The planned higher resolution curvilinear orthogonal model grid improvements planned will also consider model resolution in the eastern Sound during model development.

The Hudson River and other major tributaries will be included in the model grid upstream to a location at the head of tide or where sufficient data exist to define model inputs along with other major tributaries. Figure 5 presents the spatial modeling extents to be used for the LIS HWQMs.

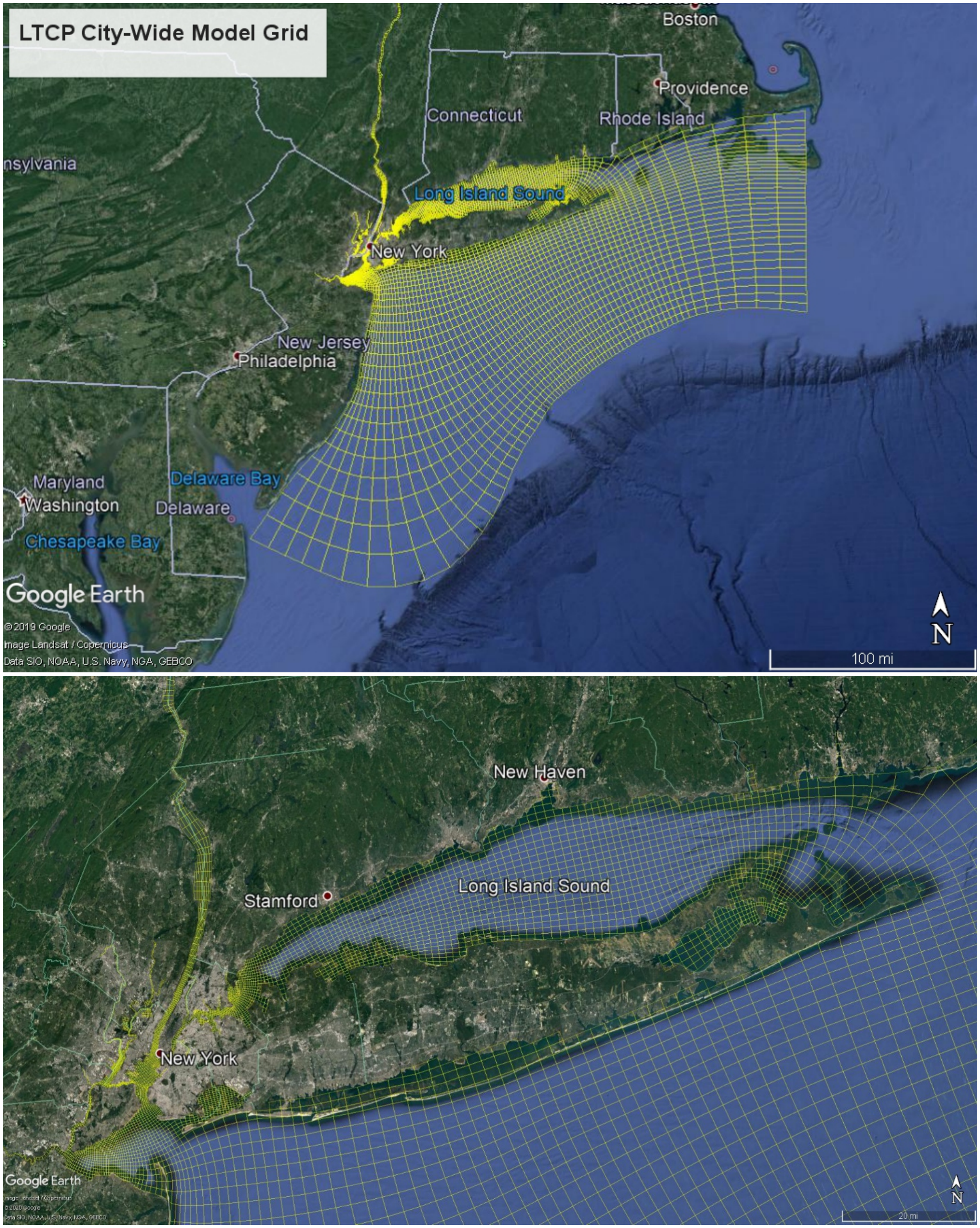

Figure 5. Proposed Spatial Extents for the LIS HWQMs

The grid resolution will be finer than that used for SWEM, expanded into embayments and up to the fall-lines of major tributaries. Grid resolution will be balanced with the computational burden created by an increased number and smaller model cells, not to mention the potential for an increased number of vertical segments. In order to develop a practical modeling tool that can be used to assess multiple management strategies, a goal will be to keep the hydrodynamic and water quality model execution times to less than 24 hours per year. The original SWEM used 10 vertical layers, which may not be adequate to reproduce the observed vertical density stratification and a factor in why vertical mixing was modified in the original application of the SWEM water quality model. Sensitivities will be conducted by adding additional vertical layers (e.g., up to 20-40) to determine if increased vertical resolution improves the model's ability to reproduce vertical stratification and to assess how many vertical layers will be required in the updated model.

As noted in O'Donnell et al. (2010 and 2014), the original SWEM had deficiencies in its ability to reproduce DO in LIS. After some preliminary testing by HDR, HDR believes a finer grid resolution will be a major factor in improving the updated model's ability to reproduce DO concentrations in LIS.

As the two embayments to be modeled are selected, an approach to developing model grids for the smaller embayments will be developed.

HDR has identified coastline and bathymetric data sources as outlined in the Data Acquisition Plan (HDR, 2021).

5.1.2 Boundary Conditions

Hydrodynamic model boundary conditions include sea surface elevation, salinity and temperature. To produce a simulation of tidal-scale circulation, including the effects of baroclinicity (stratification measure), it is necessary to define the astronomical dynamics and climatological thermodynamics prevailing in LIS and the New York Bight. The low frequency dynamics along the continental shelf are important to the circulation in LIS and the New York Bight. Hence, the cross-shelf slope of the sea surface elevation at the boundaries is highly significant.

When specifying sea surface elevation [$\eta(x,t)$] at the model open boundaries, it is convenient to decompose the elevation into three additive components:

$$\eta(x,t) = \eta_g(x) + \eta_T(x,t) + \eta_M(t),$$

where x is a generalized horizontal spatial coordinate, t represents time dependance, $\eta_g(x,t)$ represents the steady cross- and along-shelf elevation gradients that drive long-term geostrophic flow, $\eta_T(x,t)$ is the astronomical tide, and $\eta_M(t)$ represents sub-tidal meteorological forcing.

The effect of the along-shelf elevation gradient imposed at the shelf break on the barotropic circulation in the New York Bight has been studied by Hopkins and Dieterle (1983). Following the findings of Hopkins and Dieterle (1983, 1987), Blumberg and Galperin (1990) adopted the same approach to specifying the boundary elevation in a summer average circulation study in the New York Bight. Previous modeling of LIS for New York City imposed a 13-cm gradient along the northeastern Nantucket Shoals boundary, an 11-cm gradient across the Cape May shelf-break southern boundary and zero gradient along the shelf boundary, and these gradients would serve as convenient starting values for the LIS-HWQMS project. However, it should be noted that due to multiple time periods to be modeled (i.e., 1994-1995, 2003-2018, 2019-2021) and climate change resulting in increased melting of polar ice and the thermal expansion of water, it may be necessary to adjust these gradients during the modeling calibration and validation efforts. A variety of potential contemporary data sources will be explored to guide development of sea surface elevation for the Mid-Atlantic Bight, including analysis of data from the National Oceanic and Atmospheric Administration (NOAA) National Data Buoy Center (Figure 6; https://www.ndbc.noaa.gov/) and regional model and data products from the Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS; https://maracoos.org/) and the Hybrid Coordinate Ocean Model (HYCOM; https://www.hycom.org/).

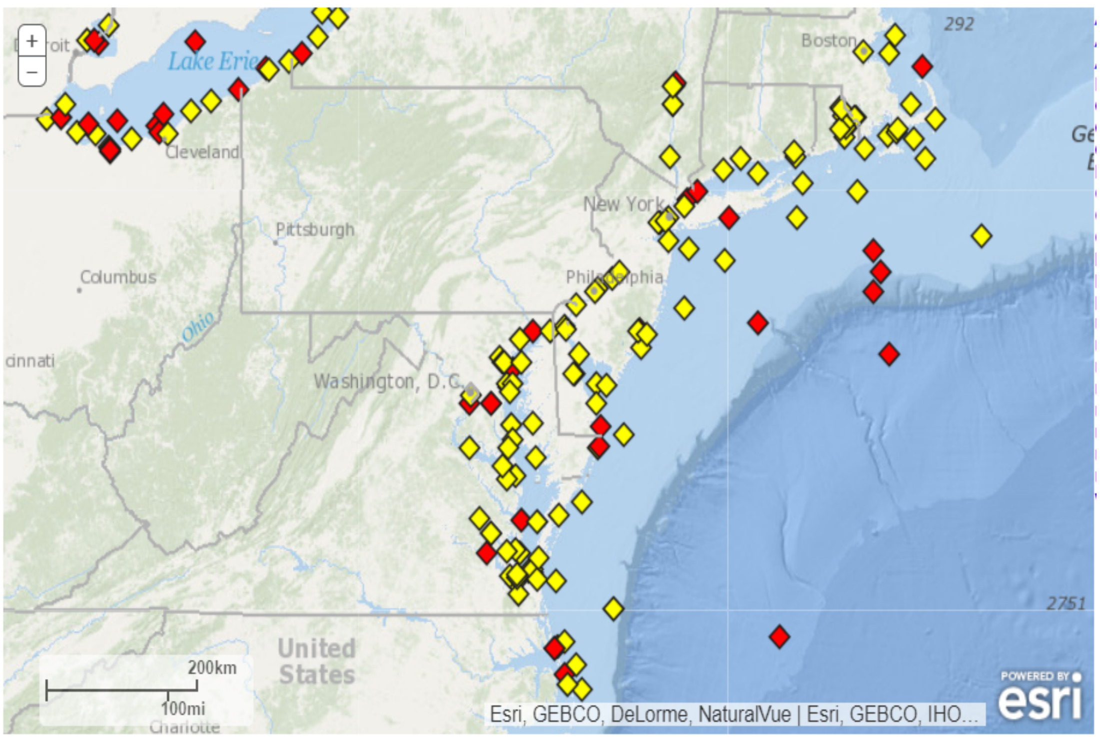

Figure 6. NOAA National Data Buoy Center

Previous LIS modeling by HDR used astronomical tide, $\eta_T(x,t)$, due to eight primary harmonic constituents (M2, S2, N2, K2, K1, O1, P1 and Q1) obtained from the global model of ocean tide (TPXO) developed by Oregon State University (Egbert et al., 1994). The input to the tidal synthesis program is gridded data of the harmonic constants with the output of η_T as a function of time and space (latitude and longitude). The tidal synthesis program uses interpolation of the tidal admittances in the diurnal and semi-diurnal bands to include nine additional minor constituents (2N2, MU2, NU2, L2, T2, J1, NO1, OO1, RHO1). The synthesis program also adds the long period constituents MF, MM, SSA using the standard equilibrium forms. However, the TXPO website (https://www.tpxo.net/home) now includes a disclaimer that TPXO global tide models are "available for academic research and other non-commercial uses" so it will be necessary to investigate whether application for municipal or regulatory purposes will be acceptable. Regardless, similar information can be extracted from the ADCIRC Tidal Databases (https://adcirc.org/products/adcirc-tidal-databases/), and HDR will pursue whichever source of tidal information is freely available for use in the LIS-HWQMS project and provides the best spatial resolution for the Mid-Atlantic Bight.

Previous modeling studies conducted by HDR (HydroQual, 2001 and 2002) indicate that the response of water surface elevation to meteorological forcing are essentially in phase throughout the New York Bight and the adjacent estuarine waters. The differences in amplitude at different locations, due to local bathymetry and coastline, are also small. Therefore, $\eta_M(t)$ will be expressed as a fraction (α) of the 35-hour low-passed water surface elevation at Sandy Hook, NJ. As a tidal wave propagates over the continental shelf, its amplitude is increased by shoaling and shallow water effects. As a result, α is expected to have a value less than one and a value of 0.5 has been determined previously by performing a series of simulation runs and comparing model results with data (HydroQual, 2001). While use of the Sandy Hook tide gauge will be the starting point for LIS HWQM, HDR will also examine model performance sensitivity to using low-frequency tide data from gauges located near the eastern end of the model domain.

Also, a modified form of the Sommerfeld radiation boundary conditions (Blumberg and Kantha, 1985) will be applied across the Cape May shelf-break section with a function that tends to force the elevation to a specified (elevation) boundary condition within a given time scale. Thus, long waves are allowed to propagate, and they are free to advect through the boundary.

Salinity and temperature boundary conditions can be obtained from a number of sources. These sources include climatological data in the World Ocean Atlas 2018 (WOA2018, https://www.nodc.noaa.gov/OC5/woa18/), and higher-resolution temperature and salinity analyses (https://www.nodc.noaa.gov/OC5/WOA01/qd_ts01.html) published by NOAA. The World Ocean Atlas dataset contains gridded monthly salinity and temperature at one-degree latitude-longitude, which is tabulated at 19 depth levels from 0 to 1,000 meters. The higher-resolution NOAA information is available on a monthly basis at ¼-degree increments. The Mid-Atlantic Ocean Climatological and Hydrographic Atlas (MOCHA) (Fleming, 2016) will also be reviewed and is available as a NetCDF file for download at http://tds.marine.rutgers.edu/thredds/catalog/other/climatology/mocha/catalog.html. The HYCOM model (https://www.hycom.org/) GOFS 3.1 41 layer HYCOM + NCODA Global 1/12° Analysis and Reanalysis can also be used to assign salinity and temperature. At the model boundary, salinity and temperature will be linearly interpolated from the surrounding gridded data.

As climatological data do not represent true monthly variations of salinity and temperature for the four modeling time periods, it may be necessary to adjust the initially defined boundary conditions so that calculated salinity and temperature match the monthly mean salinity and temperature in the LIS study area.

Once the two embayment models are selected, the preferred approach for assigning offshore boundary conditions is to use the open waters LIS model output for water elevation, salinity and temperature model inputs.

5.1.3 Freshwater Flows

Freshwater inputs will be assigned to define the sources, volumes, and timing of freshwater discharges to LIS. These sources include rivers, wastewater resource recovery facilities (WRRFs), combined sewer overflows (CSOs), stormwater and groundwater. The time interval assigned to the model input will depend on the frequency of available information and the size of the model input files. Previous models of LIS contain over 1,000 freshwater sources. Initially, flows will be assigned on a daily basis with the exception of groundwater, which will be assigned on an annual or seasonal basis. Potentially, CSOs and stormwater could be assigned on an hourly basis, but due to the relative scale of these flows to the size of LIS, hourly flows do not appear necessary at this time.

River flows are available from the USGS gages identified in the Data Acquisition Plan. In some cases, the gages do not include the entire drainage area, so the flows will be adjusted by a ratio of gaged to ungaged area. It is anticipated that these river gages will be used to develop model inputs, but an updated USGS gage query will be completed as part of the model setup process.

Flows will be supplied by DEP for the 14 WRRFs for the modeling time periods, along with CSO, stormwater and direct runoff flow volumes from DEP InfoWorks models of the 14 WRRF sewershed areas. New York State Department of Environmental Conservation (NYSDEC), CTDEEP, Rhode Island Department of Environmental Management (RIDEM), and New Jersey Department of Environmental Protection (NJDEP) will also be contacted to obtain available data on CSO, stormwater and direct runoff discharges to LIS and the Hudson River.

Additional flows will be based on data from DEC, CTDEEP, RIDEM, NJDEP and EPA for point-source dischargers (municipal and industrial) greater than 1 million gallons per day (MGD)). For the embayment models, point source dischargers with a flow less than 1 MGD will be considered if they are locally important.

CTDEEP is currently updating its Hydrological Simulation Program Fortran (HSPF) watershed model for the watersheds that discharge into LIS. Output from this model could potentially be used to assign river flows and coastal runoff from Connecticut, depending on its final completion and availability. HDR will be cautious in its application of methods for model inputs so the approach used for developing model inputs is consistent between the calibration, validation, and post-audit periods.

In previous NYC area modeling analyses, HDR has used the time-variable RAINMAN rainfall-runoff model (similar to the rational runoff method) to estimate runoff flows for areas without data. This approach can still be used if data are not found for watershed areas that discharge to the model domain and do not have sufficient data to develop model inputs.

5.1.4 Meteorological Inputs

Meteorological inputs will be applied at the water surface for wind stress and heat flux. Wind stress is calculated from wind speed and wind direction. Heat flux computations require the specification of air temperature, relative humidity, barometric pressure, shortwave solar radiation or cloud cover, and water column light-extinction coefficients.

With the exception of light-extinction coefficients, these parameters will be extracted from the NOAA's North American Regional Reanalysis (NARR) dataset (www.esrl.noaa.gov/psd/data/gridded/data.narr.html). The NARR dataset consists of 32-kilometer resolution gridded data at 3-hour intervals. Local airport data can also be used to supplement the NARR dataset. Cloud-cover data (or best estimates) will be used with clear-sky latitude-dependent estimates of solar radiation data to estimate solar radiation data for input to the hydrodynamic and water quality model where observed solar radiation is not available.

The NOAA High Resolution Rapid Refresh (HRRR) model has hourly meteorological output on a 3-km resolution beginning in late 2014, and these data may be applied as well after reviewing the various available data sources (https://rapidrefresh.noaa.gov/hrrr/).

Meteorological inputs will be varied spatially and temporally based on the chosen dataset.

5.1.5 Model Code

Modeling will begin with the publicly available version of the hydrodynamic model code and modified as needed for the LIS-HWQMS project. Code development during the project will be tracked using Git. Hardware design and configuration requirements for data storage, model execution and data processing will be the subject of a separate project deliverable. Locations for obtaining source code for each model is presented in Attachment 1 – Hydrodynamic Model Fact Sheets.

5.2 Water Quality Model

Water quality model inputs include the calculated hydrodynamic tidal transport, boundary conditions, point and nonpoint source loads, time-variable functions and kinetic constants. At a minimum, the water quality model will include the following parameters:

- Particulate organic nitrogen (including labile and refractory fractions);
- Dissolved organic nitrogen (including labile and refractory fractions);
- Ammonia nitrogen;
- Nitrite plus nitrate nitrogen;
- Particulate organic phosphorus (including labile and refractory fractions);
- Dissolved organic phosphorus (including labile and refractory fractions);
- Dissolved inorganic phosphorus (orthophosphate);
- Particulate organic carbon (including labile and refractory fractions);
- Dissolved organic carbon (including labile and refractory fractions);
- Biogenic silica;
- Available dissolved silica;
- Phytoplankton carbon or chlorophyll-a (multiple algal groups);
- Dissolved oxygen; and

- Inorganic suspended solids.

Additional state-variables will be considered and added as needed depending on the available supporting data. These state-variables could include inert fractions of organic matter and particulate inorganic phosphorus.

In addition, the water quality model must include a SFM for the calculation of sediment oxygen demand (SOD) and sediment nutrient fluxes as a function of settled particulate organic matter and overlying water column concentrations. A brief description of the SFM is provided in Section 2.2.

The number of algal groups used in the water quality model will be based on analysis of available phytoplankton data and chlorophyll-a variability. A preliminary assessment of water quality data suggests that two functional groups may be adequate and include a winter diatom group and a mixed summer assemblage.

5.2.1 Hydrodynamic Transport

In many coupled HWQMs, the water quality model is run “de-coupled” with saved hydrodynamic model transport output rather than running both the hydrodynamic and water quality models at the same time. This is because of the added runtime due to completing hydrodynamic and water quality calculations at the same time.

Typically, in the case of de-coupled hydrodynamic-water quality models, the hydrodynamic model transport output is averaged over some time interval (e.g., 1-hour) before use in the water quality model. Additional testing will be completed to determine whether using 30-minute or 15-minute averaging intervals improves water quality model results and to determine the best method for averaging (e.g., arithmetic mean, median, harmonic mean).

5.2.2 Boundary Conditions

Water quality model boundary condition locations are the same as those used in the hydrodynamic model (i.e., offshore tidal locations). At these boundary condition locations, model inputs are required for all parameters used in the water quality model (e.g., organic nitrogen, ammonia nitrogen, nitrite plus nitrate nitrogen) as time-series inputs for the modeling time period under consideration.

As described earlier, World Ocean Atlas 2018 information is available that can be used to assign open water boundary conditions. Available constituents include DO, nitrate, phosphate, and silica. NOAA’s Northeast Fisheries Science Center provides semi-annual reports on sea surface temperature, chlorophyll-a and zooplankton biomass in the mid-Atlantic Bight and Southern New England from 2006 to the current time period (https://apps-nefsc.fisheries.noaa.gov/nefsc/current-conditions/). EPA’s Water Quality Portal (https://www.epa.gov/waterdata/water-quality-data-download#portal) is another potential source for data that can be used to assign open water boundary conditions. Battelle’s original sampling during 1994 and 1995 to support the original development of SWEM can also provide guidance to the assignment of open water boundary condition concentrations.

In addition, Fennel et al. (2006) describe several data sources from the 1980s through 2004 that were used to compile monthly climatology data sets of biogeochemical variables including chlorophyll-a, nitrate and ammonium for comparison to the ROMS biogeochemical model. Fennel et al. delineated station data along the 50-meter isobath as “Inner” and “Outer” Middle Atlantic Bight regions for model-data comparisons.

Other data sources available for developing boundary conditions are presented in the Nutrient Module of the EPA New York Bight Restoration Plan by HydroQual (1991). This report compiled an inventory of the historical hydrographic and water quality data for the New York Bight from the mid-1950s through 1986 with the largest amount of data collected after the mid-1970s. This historical data was used to develop USACE hydrodynamic and water quality models of the New York Bight (Scheffner et al., 1994; Hall and Dortch, 1994). The files include records obtained from Brookhaven National Laboratory (BNL), EPA STORET, NOAA NODC and NOAA NMFS research programs (MESA NY Bight, NEMP, MARMAP) (Stoddard et al., 1986).

While data may be limited to assign some specific boundary condition concentrations, it is anticipated that open water boundary condition concentrations are generally small and do not have a large influence on the main area of interest in western LIS. Exceptions are DO concentrations, which should be near saturation and can be derived from temperature and salinity, and DOC, which is mainly refractory such that it may not significantly impact DO concentrations.

Available water quality data near the model boundary condition locations will be used and interpolated as needed to develop time-series inputs. Internal monitoring data may also be used to aid in defining these inputs.

The preferred approach for developing offshore boundary condition inputs for the embayment models is to use output from the open waters LIS model.

5.2.3 Loads

The model loading setup for the WY1995 initial calibration time period will be based on the original SWEM loadings. The original model loading files will be retrieved from archived backups, and the model loads will be redistributed into the new finer resolution LIS model grid. Water quality model loads will be setup for the loading source flow inputs assigned in the hydrodynamic model. These WY1995 loads may also be revised to reflect updated load-development methodologies or improved data from this time period for developing the loads.

Water quality model loads for the other modeling time periods (2003-2010, 2011-2018 and 2019-2022) will be initially setup using many of the approaches used in the SWEM modeling, with some modifications based on available data sources and models. Modeling is an iterative process, and as such, the loading development approaches may need to be modified to improve the water quality models ability to reproduce the available monitoring data. The WY1995 calibration will be revisited if the loading-development methodology for the other periods deviates significantly from the approach used for the initial calibration period. The loading-development approach may need to be inconsistent between the WY 1995 and other periods if the required data are not available for WY 1995.

WRRF loads will be based on available facility records obtained from public entities such as DEP, DEC, IEC, NJDEP, NJHDG, CTDEEP, RIDEM and EPA. The frequency of assigning loading (e.g., daily, monthly) will depend on the frequency of available measurements. Since facilities do not always measure all of the state-variables included in water quality models, certain assumptions based on available data will be needed to develop loads for all water quality model parameters. The starting load setup assumption will be based on the methods used in the original SWEM development.

The original SWEM modeling included 28 tributaries and may be expanded to add additional minor tributaries. Water quality concentrations from available USGS sites can be used together with USGS gage flow to create loads for each gaged river watershed. This can be accomplished by: interpolating between concentration measurements to calculate daily loads from daily flow data; developing concentration versus flow relationships to fill in daily concentrations using the resulting relationships; developing monthly or seasonal loading concentrations by pooling concentrations from multiple years for each period and calculating daily loads with flow varying daily and concentrations varying seasonally or monthly; or by using a load estimation program such as the USGS LOADEST program.

Coastal watershed loads to LIS will be required for the smaller watersheds draining directly to LIS and coastal embayments along the Connecticut coastline and the north shore coastline of Long Island that are not represented by a major river load model input. It is anticipated that the Nutrient Load Models (NLM) developed by UConn for the Connecticut and Long Island coastal watersheds and NLMs developed for the north shore of Long Island developed as part of Suffolk and Nassau County watershed planning will be used to determine annual or seasonal loads. Currently these NLMs are developed for total nitrogen (TN), and an approach will be developed to calculate loads for other important model inputs (e.g., phosphorus, carbon). These coastal watershed loads will include groundwater sources where important (e.g., north shore of Long Island).

There is existing and on-going development of groundwater models in CT and on LI that can be used to define groundwater flows and loads. The results from these projects that are currently available or when become available will be reviewed and used to develop groundwater loads as needed.

DEP has committed to providing output from its InfoWorks models for the DEP 14 WRRFs that will include flow volumes for CSO and stormwater sources. Available flow volume information for CSO and stormwater sources from other municipalities with discharges to the LIS study area will also be obtained. HDR will use available CSO and stormwater monitoring data to apply discharge concentrations (e.g., event mean concentration) to the CSO and stormwater flows to develop these loads.

CTDEEP is currently updating its HSPF watershed model for watersheds that discharge into LIS. Output from this model could potentially be used to assign river and coastal loads from Connecticut, depending on its final completion and availability. HDR will be cautious in its application of methods for model inputs so the approach used for developing model inputs is consistent between the calibration, validation, and post-audit periods.

The SWEM monitoring program collected atmospheric data that was used to develop atmospheric loadings. The database includes DOC, NH4, NO2+NO3, TDN, DON, PO4, TDP, DOP and SiO4.These data will be reviewed to see if they are still valid for the modeling time periods. The National Atmospheric Deposition Program (NADP) (NTN Data (wisc.edu)) has atmospheric monitoring data for ammonium, nitrate and TN that will be used to estimate dry and wet atmospheric deposition loads along with rainfall data to water surface areas. EPA's Community Multiscale Air Quality Modeling System (CMAQ) output could be used to supply ammonium and nitrate deposition rates for developing atmospheric deposition loads and will be compared to the loads developed using the NADP data. CMAQ provides hourly and daily output and has created annual loads on a 12-km grid for 2002-2012. The output is separated into wet and dry deposition. Much less information is available for phosphorus atmospheric deposition rates, but available data indicates the ratio of N to P deposition is well above the Redfield ratio. Since the LIS is nitrogen or silica limited, uncertainty in the P deposition rate will not affect the modeling outcome since it is found in excess in the water column.

The original SWEM atmospheric input was based on wet-fall concentrations and rainfall and was applied monthly. The goal would be to apply atmospheric loads at least on a monthly basis. The initial approach would be to use annual average dry-deposition with a wet-deposition that varies based on rainfall.

Coastal erosion is another potential source of loading but has not generally been discussed in terms of nutrients. HDR will review available studies (e.g., https://www.somas.stonybrook.edu/2018/10/16/workshop-on-the-erosion-of-long-islands-north-shore/). This will allow an assessment of whether these loads (nutrients and solids) are significant in LIS and embayments and whether they should be assigned in the model.

5.2.4 Time-Variable Inputs

Time-variable model inputs vary over time and can include the daily amount of solar radiation, length of daylight, and wind speed as it affects calculation of atmospheric reaeration. A time and spatially variable base light-extinction coefficient can also be applied. This base light-extinction coefficient is then modified by phytoplankton (chlorophyll-a), colored dissolved organic matter (CDOM), DOC, detrital POM and/or ISS as applied in the model kinetics. The form of the light extinction relationship to chlorophyll-a and other constituents will be determined during model development.

Solar radiation will be applied based on the values used in the hydrodynamic model from the NARR data. The hydrodynamic model either uses available solar radiation data or calculates it using available cloud cover data and clear-sky, latitude-dependent estimates of solar radiation. Initially, solar radiation will be assigned as one value over the entire model domain, but due to the size of the model domain, a two-dimensional (horizontal variable) time-variable function may be needed to represent spatial differences in the LIS study area.

Fraction of daylight input provides the model with how long the sun shines on a given day and will be estimated given the central latitude of the model study area.

Wind speed can be used to calculate atmospheric reaeration rates (per time units) in addition to using surface current speeds calculated by the hydrodynamic model. If wind speed is used, it will be transferred from the hydrodynamic model to the water quality model for use in calculating atmospheric reaeration. In some instances, an oxygen transfer coefficient (length per time units) may be used that can be assigned as spatially varying.

Base light-extinction coefficients define the reduction of surface light with depth and can be estimated from Secchi depth data or vertical measurement of photosynthetically available radiation (PAR) during periods with low chlorophyll-a and TSS concentrations or based on pure water. In addition, the base light-extinction coefficients can be corrected for estimates of interference from chlorophyll-a and ISS. The base light-extinction coefficients can vary over time due to ambient conditions (e.g., turbidity) as well as vary spatially. It is expected that base light-extinction coefficients will be setup as a two-dimensional (horizontally variable) time-variable function. These base light-extinction coefficients are then modified by the model calculated chlorophyll-a and other constituents (e.g., ISS) as applied in the model kinetics.

5.2.5 Kinetic Constants

Parameters and constants define the rates for various model parameter transformation pathways (e.g., algal growth and respiration, ammonia nitrification, carbon oxidation), among other things. Parameters and constants are often based on literature values, prior modeling efforts and best professional judgment. Previous SWEM modeling will provide a starting point for many parameters and constants, as SWEM was calibrated to the 1994-1995 dataset with further adjustments made during the additional model calibration (2003-2010) and validation (2011-2018) modeling efforts.

Special study data collected since the SWEM 1994-1995 modeling, such as for algal growth and respiration, will provide additional information for refining these parameters and constants.

5.2.6 Model Code

Modeling will begin with the publicly available version of the water quality model code and the code will modified as needed for the LIS-HWQMS project. Code development during the project will be tracked using Git. Hardware design and configuration requirements for data storage, model execution and data processing will be the subject of a separate project deliverable. The location of each water quality model source code can be found in Attachment 2 in the Water Quality Model Fact Sheets.

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1

Hydrodynamic Model Fact Sheets

Model Fact Sheet

Model Name:	Adaptive Hydraulics 3D Shallow Water (AdH-SW3)
Developer:	US Army Engineer Research and Development Center
Current Version:	4.6+
Contact:	https://www.erdc.usace.army.mil/Locations/CHL/AdH/Documentation/

<table>
<tr><td>Model Description</td><td colspan="2">Adaptive Hydraulics (AdH) numerical code is a modular, parallel, adaptive finite-element model for one-, two- and three-dimensional (2D, and 3D)l flow and transport. AdH simulates groundwater flow, internal flow and open channel flow. AdH was developed in the Engineer Research and Development Center's Coastal and Hydraulics Laboratory. AdH is a high fidelity computational tool capable of simulating estuarine and riverine flows, hydrodynamics in reservoirs, and lakes, flows due to dam and levee breaches, continental scale flows, flows due to compound flooding, non-hydrostatic free surface flows, and all associated transport phenomenon.

AdH is linked to the mixed grain sediment transport library, SEDLIB, for sediment transport and the simulation of morphological evolution of hydrodynamic systems.

Water quality simulations in AdH are achieved via linkages to the Nutrient Sub Model (NSM) processes library, and the ICM kinetics processes library.

AdH is capable of baroclinic flows such as those impacted by salinity and temperature in 2D as well as 3D.

The 2D module of AdH can be executed in a quasi-3D model to take advantage of the helical flow correction. This correction allows AdH to accurately simulate flows in river bends, or other areas where helical flow occurs.

AdH executables are available to everyone at no cost. In the near future, the AdH source code will be open-sourced. Open Sourcing is contingent upon appropriate approvals being obtained.

Applications: Galveston Bay (2015), Sacramento River and Mobile Bay</td></tr>
<tr><td>Model Availability</td><td colspan="2">☐ Public Doman w/ Source ☒ Public Domain w/o Source</td></tr>
<tr><td>Number of Dimensions</td><td colspan="2">☒ 1D ☒ 2D ☒ 3D</td></tr>
<tr><td>Water Body Type</td><td colspan="2">☒ River ☒ Lake ☒ Estuary/Coastal</td></tr>
<tr><td>Temporal Variability</td><td colspan="2">☐ Steady-State ☒ Dynamic</td></tr>
<tr><td>Heat Balance</td><td colspan="2">☐ Temperature Mass Balance ☒ Full Heat Exchange</td></tr>
<tr><td colspan="2">Model Input Data Needs</td><td>Model Features</td></tr>
</table>

• Water body coastline and bathymetry • Meteorological data (air temperature, wind speed/direction, solar radiation, relative humidity and atmospheric pressure) • Freshwater inflow, temperature and salinity • Boundary tidal water elevation, temperature and salinity • Point and nonpoint source inputs (flow and temperature) • Bottom friction coefficients, vertical and longitudinal dispersion coefficients • Hydraulic structures	• Linear triangle-based meshing allows for accurate and adequate representation of bathymetry. • Vertical meshing that is neither Sigma or Z-grid based and, hence, is not encumbered by the drawbacks of either. • Run-time adaption in the horizontal and vertical allows for accurate representation of hydrodynamics as well as transport. • Internal time-step size adaption allows for time-step changes to capture rapidly changing physics during run time. • Fluid and constituent mass are conserved. • Easy transition is accomplished from the 2D realm to the 3D realm. • Wetting and drying • • vessel movement, ice cover, the influence of bridge decks, the influence of culvert entrances and the presence of flow control structures such as weirs, flap and sluice gates, etc. • Only 2D manual on-line References: Savant. G. and R.C. Berger. 2015. Three-Dimensional Shallow Water Adaptive Hydraulics (ADH-SW3) Validation Report 1: Galveston Bay Hydrodynamics and Salinity Transport. ERDC/CHL TR-15-3.

Model Fact Sheet

Model Name:	Curvilinear-Grid Hydrodynamics 3D Model (CH3D)
Developer:	Dr. Y. Peter Sheng
Current Version:	CH3D-IMS
Contact:	https://aces.coastal.ufl.edu/CH3D/

<table>
<tr><td>Model Description</td><td colspan="2">CH3D is a Curvilinear-grid Hydrodynamics 3D model developed originally by Dr. Y. Peter Sheng at the Aeronautical Research Associates of Princeton, Inc. during 1983-1986. Since 1989, Dr. Sheng's group (Advanced Coastal Environmental Simulations Lab) at the University of Florida has substantially enhanced the processes, numerical algorithms, and coding of the CH3D model through numerous studies on complex shallow estuaries and lakes. The CH3D model uses a horizontally boundary-fitted curvilinear grid and a vertically sigma grid, and hence is suitable for application to coastal and nearshore waters with complex shoreline and bathymetry. The model contains a robust turbulence closure model which enables accurate simulation of stratified flows in estuaries and lakes. Recent enhancements of the model include modeling of aquatic vegetation, modeling of moving shoreline, addition of a sediment transport model, addition of a water quality model, and addition of a light/seagrass model, and parallel computing.
Applications include: USACE ERDC feasibility modeling study of the New York Bight (Scheffner et al., 1994) as well as academic research projects (Sheng et al., 2009)</td></tr>
<tr><td>Model Availability</td><td colspan="2">☐ Public Doman w/ Source ☒ Public Domain w/o Source</td></tr>
<tr><td>Number of Dimensions</td><td colspan="2">☐ 1D ☐ 2D ☒ 3D</td></tr>
<tr><td>Water Body Type</td><td colspan="2">☐ River ☒ Lake ☒ Estuary/Coastal</td></tr>
<tr><td>Temporal Variability</td><td colspan="2">☐ Steady-State ☒ Dynamic</td></tr>
<tr><td>Heat Balance</td><td colspan="2">☒ Temperature Mass Balance ☐ Full Heat Exchange</td></tr>
<tr><td colspan="2">Model Input Data Needs</td><td>Model Features</td></tr>
<tr><td colspan="2">• Water body coastline and bathymetry
• Meteorological data (air temperature, wind speed/direction, solar radiation, relative humidity and atmospheric pressure)
• Freshwater inflow, temperature and salinity
• Downstream boundary tidal water elevation, temperature and salinity
• Point and nonpoint source inputs (flow and temperature)
• Bottom friction coefficients, vertical and longitudinal dispersion coefficients</td><td>• Capable of representing multi-dimensional, dynamic tidal circulation (salinity, temperature, water elevation and currents) with the full simulation of atmospheric/water heat exchange
• Detailed features include:
  • Solution of full momentum, continuity, salinity, temperature and density equations
  • Sigma coordinate representation of vertical component
  • Curvilinear orthogonal coordinate representation of horizontal component
  • Imbedded second-order turbulence closure
  • Full simulation of density (baroclinic) terms in 3D (salinity and temperature)
  • Efficient parallelization of source code</td></tr>
</table>

	References: Scheffner, N., S.R. Vemulakonda, D. Mark, L. Butler and K. Kim .1994. New York Bight Study, Report 1: Hydrodynamic Modeling, U.S. `Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS, Technical Report CERC-94-4 August. Sheng, P., et al. 2009. Skill assessment of an integrated modeling system for shallow coastal and estuarine ecosystems, Journal of Marine Systems, Volume 76, Issues 1–2, 2009, Pages 212-243, ISSN 0924-7963, https://doi.org/10.1016/j.jmarsys.2008.05.011.

Model Fact Sheet

Model Name:	Delft3D-FLOW
Developer:	Deltares
Current Version:	v6.03
Contact:	https://oss.deltares.nl/web/delft3d/download

Model Description	Delft3D-FLOW is a module included in a fully integrated computer software suite for a multi-disciplinary approach and 3D computations for coastal, river and estuarine areas developed by Deltares. This software suite can carry out simulations of flows, sediment transport, waves, water quality, morphological development and ecology. The Delft3D suite is composed of several modules, grouped around a mutual interface, while being capable to interact with one another. Delft3D-FLOW is a multi-dimensional (2D or 3D) hydrodynamic (and transport) simulation program which calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on a rectilinear or a curvilinear, boundary fitted grid. In 3D simulations, the vertical grid is defined following the sigma coordinate approach. The hydrodynamic conditions (velocities, water elevations, density, salinity, vertical eddy viscosity and diffusivity) calculated are used as input to the other Delft3D modules. Currently, the full source code is available for Delft3D-FLOW (including morphology), Delft3D-WAVE, DELWAQ (D-Water Quality and D-Ecology) and PART (D-Particle Tracking) engines under GPLv3 conditions. Code revisions, knowledge updates and new features can be shared by registering with Deltares. Applications: Baird, Gowanus Canal Superfund Study, https://www.baird.com/case-studies/gowanus-canal-superfund-study/ and Bennet, Mulligan and Hapke (2018) Hurricane Sandy, Great South Bay, Continental Shelf Research, 161:1-11, https://doi.org/10.1016/j.csr.2018.04.003	
Model Availability	☒ Public Doman w/ Source ☐ Public Domain w/o Source	
Number of Dimensions	☐ 1D ☒ 2D ☒ 3D	
Water Body Type	☒ River ☒ Lake ☒ Estuary/Coastal	
Temporal Variability	☐ Steady-State ☒ Dynamic	
Heat Balance	☐ Temperature Mass Balance ☒ Full Heat Exchange	
Model Input Data Needs		Model Features

• Water body coastline and bathymetry
• Meteorological data (air temperature, wind speed/direction, solar radiation, relative humidity and atmospheric pressure)
• Freshwater inflow, temperature and salinity
• Downstream boundary tidal water elevation, temperature and salinity
• Point and nonpoint source inputs (flow and temperature)
• Bottom friction coefficients, vertical and longitudinal dispersion coefficients
	• Capable of representing multi-dimensional, dynamic tidal circulation (salinity, temperature, water elevation and currents) with the full simulation of atmospheric/water heat exchange
	• Detailed features include:
	  • Solution of full momentum, continuity, salinity, temperature and density equations
	  • Sigma coordinate representation in vertical
	  • Curvilinear orthogonal coordinate representation of horizontal component
	  • Imbedded second-order turbulence closure scheme to represent turbulent mixing
	  • 2D/3D mode-spitting solution scheme
	  • Full simulation of density (baroclinic) terms in 3D (salinity and temperature)
	  • Efficient parallelization of source code
	References:
	Bennet, V.C.C, R.P. Mulligan, and C.J. Hapke. 2018. A numerical model investigation of the impacts of Hurricane Sandy on water level variability in Great South Bay, New York. Continental Shelf Research. Vol. 161, pp. 1-11.

Model Fact Sheet

Model Name:	Estuarine, Coastal and Ocean Model with Sediment Transport Dynamics (ECOMSED)
Developer:	HDR
Current Version:	v1.3
Contact:	https://www.hdrinc.com/services/environmental-sciences/water-quality-hydrodynamic-modeling-software

Model Description	ECOMSED is a three-dimensional hydrodynamic and sediment transport computer code developed by HDR for application to marine and freshwater systems. The development of ECOMSED has its origins in the mid-1980's with the creation of the Princeton Ocean Model followed by an upgraded version called ECOM for shallow water environments such as rivers, lakes, estuaries and coastal oceans. In the mid-1990s, concepts for sediment resuspension and settling developed by W. Lick at the University of California, Santa Barbara were incorporated within the ECOM modeling framework. The sediment transport module can predict temporal and spatial distributions of: (1) suspended sediment concentrations (cohesive and non-cohesive); (2) sediment bed elevation changes; (3) fluxes at the sediment-water interface; and (4) changes in sediment bed composition. The module can accept as input: spatially-variable sediment bed properties and time-variable sediment loading at river discharges and open boundaries. Applications: HydroQual (2001, 2002), Georgas et al. (2016) [sECOM - proprietary] for additional applications see Attachment 3.	
Model Availability	☒ Public Doman w/ Source ☐ Public Domain w/o Source	
Number of Dimensions	☐ 1D ☒ 2D ☒ 3D	
Water Body Type	☒ River ☒ Lake ☒ Estuary/Coastal	
Temporal Variability	☐ Steady-State ☒ Dynamic	
Heat Balance	☐ Temperature Mass Balance ☒ Full Heat Exchange	

Model Input Data Needs	Model Features

• Water body coastline and bathymetry
• Meteorological data (air temperature, wind speed/direction, solar radiation, relative humidity and atmospheric pressure)
• Freshwater inflow, temperature and salinity
• Boundary tidal water elevation, temperature and salinity
• Point and nonpoint source inputs (flow and temperature)
• Bottom friction coefficients, vertical and longitudinal dispersion coefficients
	• Capable of representing multi-dimensional, dynamic tidal circulation (salinity, temperature, water elevation and currents) with the full simulation of atmospheric/water heat exchange
	• Detailed features include:
	  • Solution of full momentum, continuity, salinity, temperature and density equations
	  • Sigma coordinate representation of vertical component
	  • Curvilinear orthogonal coordinate representation of horizontal component
	  • Imbedded second-order turbulence closure scheme to represent turbulent mixing
	  • 2D/3D mode-spitting solution scheme
	  • Full simulation of density (baroclinic) terms in 3D (salinity and temperature)
	  • Efficient parallelization of source code

	• Cohesive and non-cohesive sediment transport. References: Georgas, N., L. Yin, Y. Jiang, Y. Wang, P. Howell, V. Saba, J. Schulte, P. Orton and B. Wen .2016. An open-access, multi-decadal, three-dimensional, hydrodynamic hindcast dataset for the Long Island Sound and New York/New Jersey Harbor estuaries, J. Mar. Sci. Eng, 4, 48; doi:10.3390/jmse4030048. HydroQual, Inc., 2001. 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 City of New York Department of Environmental Protection. HydroQual, Inc., 2002. Calibration Enhancement of the System-Wide Eutrophication Model (SWEM) in the New Jersey Tributaries, Report prepared for New Jersey Department of Environmental Protection under agreement with the Passaic Valley Sewerage Commissioners.

Model Fact Sheet

Model Name:	Environmental Fluid Dynamics Code (EFDC)
Developer:	J.M. Hamrick, TetraTech
Current Version:	v1.01
Contact:	https://www.epa.gov/ceam/environmental-fluid-dynamics-code-efdc (EFDCepa)

Model Description	EFDC is a state-of-the-art hydrodynamic model that can be used to simulate aquatic systems in one, two, and three dimensions. It solves three-dimensional, vertically hydrostatic, free surface, turbulent averaged equations of motion for a variable-density fluid. The physics of the EFDC model and many aspects of the computational scheme are equivalent to the widely used Blumberg-Mellor model. The primary support for the initial development of EFDC was provided by the Commonwealth of Virginia (Virginia Institute of Marine Science). Prior to 1996, additional funding for the continued development of the EFDC model was provided by USEPA through a grant to the Virginia Institute of Marine Science. Subsequent to 1996, primary support for the development and maintenance of EFDC was provided by various USEPA programs and by Tetra Tech, Inc. Three versions of the EFDC model are available: (1) EFDCepa; (2) SNL-EFDC; and (3) EFDC+. Applications: Peconic Estuary (Tetra Tech, 2000, 2005); Norwalk Harbor (Tetra Tech, 1995); and the Delaware River Estuary (Philadelphia Water Department, 2015). Embayment models of hydrodynamics for the North Shore of Long Island in support of the NYS DEC Long Island Nitrogen Action Plan (LINAP) (Wilson, 2018).	
Model Availability	☐ Public Doman w/ Source ☒ Public Domain w/o Source (EFDCepa, EFDC+)	
Number of Dimensions	☒ 1D ☒ 2D ☒ 3D	
Water Body Type	☒ River ☒ Lake ☒ Estuary/Coastal	
Temporal Variability	☐ Steady-State ☒ Dynamic	
Heat Balance	☐ Temperature Mass Balance ☒ Full Heat Exchange	
Model Input Data Needs		Model Features

• Water body coastline and bathymetry
• Meteorological data (air temperature, wind speed/direction, solar radiation, relative humidity and atmospheric pressure)
• Freshwater inflow, temperature and salinity
• Boundary tidal water elevation, temperature and salinity
• Point and nonpoint source inputs (flow and temperature)
• Bottom friction coefficients, vertical and longitudinal dispersion coefficients
	• Capable of representing multi-dimensional, dynamic tidal circulation (salinity, temperature, water elevation and currents) with the full simulation of atmospheric/water heat exchange
	• Detailed features include:
	  ◦ Solution of full momentum, continuity, salinity, temperature and density equations
	  ◦ Sigma and sigma-Z coordinate representation of vertical component
	  ◦ Curvilinear orthogonal coordinate representation of horizontal component
	  ◦ Imbedded second-order turbulence closure scheme to represent turbulent mixing
	  ◦ 2D/3D mode-spitting solution scheme
	  ◦ Full simulation of density (baroclinic) terms in 3D (salinity and temperature)
	  ◦ Efficient parallelization of source code
	
	References:
	
	Philadelphia Water Dept. 2015. Tidal Waters Water Quality Model- Bacteria and Dissolved Oxygen. Consent Order & Agreement Deliverable IX and X. City of Philadelphia Combined Sewer Overflow Long Term Control Plan Update, Philadelphia Water Department, Philadelphia, PA.
	
	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. Prepared by Tetra Tech, Inc., Fairfax, VA.
	
	Tetra Tech. 2000. Three-dimensional Hydrodynamic and Water Quality Model of Peconic Estuary, Draft Final Report. Prepared for Peconic Estuary Program, County of Suffolk, Department of Health Services, Office of Ecology, Riverhead, NY. Prepared by Tetra Tech, Inc., Fairfax, VA. June 2000.
	
	Tetra Tech. 2005. Refinements to the Three-dimensional Hydrodynamic and Water Quality Model of Peconic Estuary, Draft Report. Prepared for Peconic Estuary Program, County of Suffolk, Department of Health Services, Office of Ecology, Riverhead, NY. Prepared by Tetra Tech, Inc., Fairfax, VA. March 2005.
	
	Wilson, R.E. 2018. Quality Assurance Project Plan for EFDC and FVCOM Modeling for Nassau County Long Island Embayments, prepared for NYSDEC.

Model Fact Sheet

Model Name:	SNL-Environmental Fluid Dynamics Code (EFDC)
Developer:	Sandia National Laboratories
Current Version:	2008 GNU General Public License version 2.0 (GPLv2)
Contact:	https://sourceforge.net/projects/snl-efdc/

Model Description	Sandia National Laboratories' (SNL) environmental assessment modeling tool helps optimize the design of MHK-turbine array layouts within ocean, tidal, and river systems to balance energy generation efficiency with environmental considerations. The new tool, SNL-EFDC, is an augmented version of US EPA's Environmental Fluid Dynamics Code (EFDC) and includes; (1) a new module that simulates energy conversion (momentum withdrawal) by MHK turbine-like devices including commensurate changes in the turbulent kinetic energy and turbulent kinetic energy dissipation rate, (2) new, advanced sediment dynamics routines, and (3) augmented water quality modules. SNL-EFDC has been verified and validated against flume measurements of flow around sub-scale turbines and actuator disks. SNL-EFDC is the only open source version of EFDC.
Model Availability	☒ Public Doman w/ Source ☐ Public Domain w/o Source
Number of Dimensions	☒ 1D ☒ 2D ☒ 3D
Water Body Type	☒ River ☒ Lake ☒ Estuary/Coastal
Temporal Variability	☐ Steady-State ☒ Dynamic
Heat Balance	☐ Temperature Mass Balance ☒ Full Heat Exchange

Model Input Data Needs	Model Features

• Water body coastline and bathymetry
• Meteorological data (air temperature, wind speed/direction, solar radiation, relative humidity and atmospheric pressure)
• Freshwater inflow, temperature and salinity
• Downstream boundary tidal water elevation, temperature and salinity
• Point and nonpoint source inputs (flow and temperature)
• Bottom friction coefficients, vertical and longitudinal dispersion coefficients
	• Capable of representing multi-dimensional, dynamic tidal circulation (salinity, temperature, water elevation and currents) with the full simulation of atmospheric/water heat exchange
	• Detailed features include:
	  ◦ Solution of full momentum, continuity, salinity, temperature and density equations
	  ◦ Sigma coordinate representation of vertical component
	  ◦ Curvilinear orthogonal coordinate representation of horizontal component
	  ◦ Imbedded second-order turbulence closure scheme to represent turbulent mixing
	  ◦ 2D/3D mode-spitting solution scheme
	  ◦ Full simulation of density (baroclinic) terms in 3D (salinity and temperature)
	  ◦ Simulates marshes and tidal flats
	  ◦ Simulates marine hydrokinetic energy turbines
	  ◦ Boundary layer impacts of wind generated waves.

	References: Hamrick, J.M., 2007a. The Environmental Fluid Dynamics Code: User Manual, I. Tetra Tech, Editor, US EPA: Fairfax, VA. Hamrick, J.M., 2007b. The Environmental Fluid Dynamics Code: Theory and Computation, I. Tetra Tech, Editor, US EPA: Fairfax, VA. James, S.C., E.L. Johnson, J. Barco, and J. D. Roberts. 2016. Simulating Current-energy Converters: SNL-EFDC Model Development, Verification, and Parameter Estimation. Renewable Energy SI: Tides and Waves. James, S.C., S. Lefantzi, E.L. Johnson, J. Barco, and J. D. Roberts. 2011.Verifying Marine-Hydro-Kinetic Energy Generation Simulations Using SNL-EFDC. OCEANS'11 MTS

Model Fact Sheet

Model Name:	Finite Volume Community Model (FVCOM). Formerly Finite Volume Coastal Ocean Model
Developer:	University of Massachusetts-Dartmouth and Woods Hole Oceanographic Institute
Current Version:	3.1.6
Contact:	http://fvcom.smast.umassd.edu/fvcom/

Model Description	FVCOM is a prognostic, unstructured-grid, finite-volume, free-surface, 3D primitive equation coastal ocean circulation model developed by UMASSD-WHOI joint efforts. The model consists of momentum, continuity, temperature, salinity and density equations and is closed physically and mathematically using turbulence closure submodels. The horizontal grid is comprised of unstructured triangular cells and the irregular bottom is presented using generalized terrain-following coordinates. The General Ocean Turbulent Model (GOTM) has been added to FVCOM to provide optional vertical turbulent closure schemes. FVCOM is solved numerically by a second-order accurate discrete flux calculation in the integral form of the governing equations over an unstructured triangular grid. This approach combines the best features of finite-element methods (grid flexibility) and finite-difference methods (numerical efficiency, code simplicity) and provides a better numerical representation of both local and global momentum, mass, salt, heat, and tracer conservation. Applications: Long Island Sound currents, temperature, and salinity (O'Donnell et al, 2015) and biogeochemical models for water quality management planning in Massachusetts Bay (e.g., Zhao et al., 2020) and Chesapeake Bay (Xia and Jiang, 2016; Tian, 2020).
Model Availability	☒ Public Doman w/ Source ☐ Public Domain w/o Source
Number of Dimensions	☐ 1D ☒ 2D ☒ 3D
Water Body Type	☒ River ☒ Lake ☒ Estuary/Coastal
Temporal Variability	☐ Steady-State ☒ Dynamic
Heat Balance	☐ Temperature Mass Balance ☒ Full Heat Exchange

Model Input Data Needs	Model Features
• Water body coastline and bathymetry • Meteorological data (air temperature, wind speed/direction, solar radiation, relative humidity and atmospheric pressure) • Freshwater inflow, temperature and salinity • Downstream boundary tidal water elevation, temperature and salinity • Point and nonpoint source inputs (flow and temperature) • Bottom friction coefficients, vertical and longitudinal dispersion coefficients • Permission may be required for use in commercial settings.	• Cartesian or spherical coordinate system • Hybrid vertical layering • Automatic nesting between FVCOM models • A mass-conservative wet/dry point treatment for the flooding/drying process simulation • General Ocean Turbulent Model modules for optional vertical turbulent mixing schemes • 4D nudging and Reduced/Ensemble Kalman Filters for data assimilation • Fully-nonlinear ice models and 3D sediment transport module • MPI parallelization • Post-processing tools

	References: O'Donnell, J., G. McCardell, R. Horwitz, T. Fake, and A Cifuentes-Lorenzen .2015. Physical Oceanography of Eastern Long Island Sound Region: Modeling. Report to the CT Dept. of Transportation. Tian, R. 2020. Factors Controlling Hypoxia Occurrence in Estuaries, Chester River, Chesapeake Bay. Water 2020, 12, 1961; doi:10.3390/w12071961. Xia, M. and L. Jiang. 2016. Application of an Unstructured Grid-Based Water Quality Model to Chesapeake Bay and Its Adjacent Coastal Ocean. J. Mar. Sci. Eng. 2016, 4, 52; doi:10.3390/jsme4030052. Zhang, Y., C. Chen, P. Xue, R.C. Beardsley and P.S.J. Franks. A view of physical mechanisms for transporting harmful algal blooms to Massachusetts Bay. Marine Pollution Bulletin 154 (2020) 111048.

Model Fact Sheet

Model Name:	Regional Ocean Modeling System (ROMS)
Developer:	Dr. Hernan G. Arango - Rutgers University, Dr. Alexander F. Shchepetkin - University of California Los Angeles & Other Contributors
Current Version:	V3.7
Contact:	http://www.myroms.org/

Model Description	ROMS is a free-surface, terrain-following, primitive equations ocean model widely used by the scientific community for a diverse range of applications (physical and numerical algorithms and several coupled models for biogeochemical, sediment and sea ice applications). It also includes several vertical mixing schemes, multiple levels of nesting and composed grids. ROMS was developed in the early 2000's evolving from the S-coordinate Rutgers University Model (SCRUM). It has extensive pre- and post-processing software for data preparation, analysis, plotting, and visualization. The entire input and output data structure of the model is via NetCDF which facilitates the interchange of data between computers, user community, and other independent analysis software. Applications: Investigations in Long Island Sound (Whitney et al., 2011, 2014, 2016; Schmidt and Whitney, 2018); the Middle Atlantic Bight (Levin et al. , 2018); and Barnegat Bay (Defne et al., 2017).
Model Availability	☒ Public Doman w/ Source ☐ Public Domain w/o Source
Number of Dimensions	☐ 1D ☒ 2D ☒ 3D
Water Body Type	☒ River ☒ Lake ☒ Estuary/Coastal
Temporal Variability	☐ Steady-State ☒ Dynamic
Heat Balance	☐ Temperature Mass Balance ☒ Full Heat Exchange

Model Input Data Needs	Model Features

• Water body coastline and bathymetry
• Meteorological data (air temperature, wind speed/direction, solar radiation/cloud fraction, relative humidity and atmospheric pressure)
• Boundary tidal water elevation, temperature and salinity
• Point source inputs (river flow, temperature and salinity)
• Bottom friction coefficients, vertical and longitudinal dispersion coefficients
	• Capable of representing multi-dimensional, dynamic tidal circulation (salinity, temperature, water elevation and currents) with the full simulation of atmospheric/water heat exchange
	• Detailed features include:
	  • Solution of full momentum, continuity, salinity, temperature and density equations
	  • Terrain following sigma coordinate in the vertical
	  • Curvilinear orthogonal coordinate representation of horizontal component
	  • Turbulence closure scheme based on the level 2.5 turbulent kinetic energy equation
	  • 2D/3D mode-spitting solution scheme
	  • Full simulation of density (baroclinic) terms in 3D (salinity and temperature)
	  • Efficient parallelization of source code

	References: Defne, Z., F. Spitz, V. DePaul, and T.A. Wool .2017 Toward a Comprehensive Water-Quality Modeling of Barnegat Bay: Development of ROMS to WASP Coupler, Journal of Coastal Research 78(sp1), 34-45, https://doi.org/10.2112/SI78-004.1 Levin, Julia, John Wilkin, Naomi Fleming, and Javier Zavala-Garay. 2018. Mean circulation of the Mid-Atlantic Bight from a climatological data assimilative model, Ocean Modelling, Volume 128, Pages 1-14, ISSN 1463-5003, https://doi.org/10.1016/j.ocemod.2018.05.003. Schmidt, S.R. and M.M. Whitney. 2018. A Model Study on the Summertime Distribution of River Waters in Long Island Sound. Estuaries and Coasts 41:1002-1020. Whitney, M. M., and D. L. Codiga, 2011: Response of a large stratified estuary to wind events: Observations, simulations, and theory for Long Island Sound. J. Phys. Oceanogr., 41, 1308–1327. Whitney, M.M., Y. Jia, P.M. McManus, and C.J. Kunz .2014. Sill effects on physical dynamics in eastern Long Island Sound. Ocean Dyn., 64, 443–458, doi:10.1007/s10236-013-0681-6. Whitney, M.M., D.S. Ullman, and D.L. Codiga .2016. Subtidal exchange in eastern Long Island Sound. Journal of Physical Oceanography 46 (8), 2351–2371. https://doi.org/10.1175/JPO-D-15-0107.

2

Water Quality Model Fact Sheets

Model Fact Sheet

Model Name:	Advanced Aquatic Ecosystem Model (A2EM)
Developer:	Joseph V. DePinto, Todd Redder, and Ed Verhamme (LimnoTech)
Current Version:	1.0 (2012)
Contact:	Joseph V. DePinto and Todd Redder (LimnoTech) (734) 332-1200, jdepinto@limno.com or tredder@limno.com

Model Description	A2EM (Advanced Aquatic Ecosystem Model) is a publicly available three dimensional linked hydrodynamic-sediment transport-advanced eutrophication model developed by LimnoTech from public versions of EFDC and RCA. It models suspended solids and nutrient fate and transport, the entire low food web through zooplankton (includes up to five phytoplankton and three zooplankton functional groups) and a benthic alga functional group (e.g., *Cladophora*), two benthic filter feeder species (e.g., zebra mussels and quagga mussels), a sediment diagenesis sub-model, and dissolved oxygen kinetics. It has been applied to numerous lakes and embayments in the Great Lakes region.
Model Availability	☒ Public Doman w/ Source ☐ Public Domain w/o Source
State-variables	Salinity, TSS, DOP, POP, PO4-P, DON, PON, NH3-N, NO23-N, BSi, DSi, DOC, POC, DO, Multiple phytoplankton groups, zooplankton, benthic algae, freshwater mussels

Model Input Data Needs	Model Features

• Hydrodynamic information from hydrodynamic model (temperature, salinity, water elevation, flows, dispersion)
• Loading (point sources, non-point sources, rivers, atmospheric deposition)
• Boundary conditions
• Time-variable functions (fraction of daylight, solar radiation, etc.)
• Coefficients/constants for model kinetics
  o Plant photosynthesis and respiration
  o Nitrification, denitrification
  o Fast and slow CBOD decay rates
  o Algal stoichiometry
  o Detrital dissolution and settling
  o Hydrolysis
  o Reaeration coefficient or formulation
  o Sediment rates
	• Uses EFDC for hydrodynamics
	• Based on RCA water quality kinetics
	• Coupled to Sediment Flux Model (SFM)

Model Fact Sheet

Model Name:	AQUATOX
Developer:	Richard A. Park (Eco Modeling) & Jonathan Clough (WPC Inc.)
Current Version:	v3.2
Contact:	https://www.epa.gov/ceam/aquatox-32-download-page

Model Description	AQUATOX is a PC-based ecosystem model that predicts the fate of nutrients, sediments, and organic chemicals in water bodies, as well as their direct and indirect effects on resident organisms. AQUATOX simulates the transfer of biomass and chemicals from one compartment of the ecosystem to another by simultaneously computing important chemical and biological processes over time. AQUATOX simulates multiple environmental stressors (including nutrients, organic loadings, sediments, toxic chemicals, and temperature) and their effects on the algal, macrophyte, invertebrate, and fish communities. AQUATOX can help identify and understand the cause and effect relationships between chemical water quality, the physical environment, and aquatic life. It can represent a variety of aquatic ecosystems, including vertically stratified lakes, reservoirs and ponds, rivers and streams, and estuaries.
Model Availability	☐ Public Doman w/ Source ☒ Public Domain w/o Source Contact developer regarding source code
State-variables	DO, CBOD, NH4-N, NO23-N, NCELL, ON, TN, SRP, PCELL, OP, TP, BSi, NBSi, ISS, PHYTT, PHYTG, ALGBT, ALGBG, ZOO, FISH, SAV, BENTHICS, TEMP, SAL, pH, ALK, TIC

Model Input Data Needs	Model Features

• Receiving water characteristics
  o Geometry
  o Internal flow routing
• Time-variable inputs at boundaries and other locations (e.g., point and non-point sources)
  o Flow
  o Concentration of all state variables
• Heat sources/sinks
• Meteorological conditions
  o Solar radiation
  o Wind, air temperature
• Coefficients for
  o Plant/algal photosynthesis and respiration, algal stoichiometry
  o Oxygen demand
  o Reaeration
  o Nitrification, denitrification
  o Remineralization
  o Sediment transport
  o Toxicity
  o Sediment diagenesis
  o Invertebrate/fish life cycle and trophic interactions
	• Can be linked to EFDC hydrodynamics, but generally just for grids with a small number of cells
	• Sediment Flux Model
	• Has a Data Management System
	• PC-based
	• User Interface
	• Pre- and post-processing tools

Model Fact Sheet

Model Name:	Integrated Compartment Model (CE-QUAL-ICM / WQSTM)
Developer:	Carl F. Cerco, USACE, Engineering Research and Development Center (ERDC), Waterways Experiment Station (WES), Environmental Laboratory
Current Version:	WQSTM – Chesapeake Bay TMDL version (2010)
Contact:	https://www.erdc.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/547416/ce-qual-icm-icm/

<table>
<tr><td>Model Description</td><td colspan="2">CE-QUAL-ICM (or simply ICM) is a flexible, multi-dimensional water quality model developed by the ERDC Environmental Laboratory and suited for application in lakes, rivers, estuaries and coastal waters. ICM represents multiple biogeochemical cycles, including the aquatic carbon cycle, nitrogen cycle, phosphorus cycle and oxygen cycle. ICM also simulates physical factors, including salinity, temperature and suspended solids. The structure allows variables to be activated or inactivated and facilitates the addition of specific features required by individual projects.

ICM was initially developed as one component of a model package employed to study eutrophication processes in Chesapeake Bay. ICM stands for "integrated compartment model," which is analogous to the finite volume numerical method. The model computes constituent concentrations resulting from transport and transformations in well-mixed cells that can be arranged in arbitrary one-, two-, or three-dimensional configurations. The model computes and reports concentrations, mass transport, kinetics transformations, and mass balances.</td></tr>
<tr><td>Model Availability</td><td colspan="2">☒ Public Doman w/ Source ☐ Public Domain w/o Source</td></tr>
<tr><td>State-variables</td><td colspan="2">DO, Org-C, NH4-N, NO23-N, ON, TN, SRP, OP, TP, BSi, NBSi, ISS, PHYTT, PHYTG, ALGBT, ALGBG, ZOO, SAV, TEMP, SAL, Macrophytes</td></tr>
<tr><td colspan="2">Model Input Data Needs</td><td>Model Features</td></tr>
<tr><td colspan="2">• Hydrodynamic inputs
• Loads (point sources, non-point sources, rivers, atmospheric)
• Kinetic coefficients for
  ○ Plant photosynthesis and respiration
  ○ Nitrification, denitrification
  ○ Fast and slow CBOD decay rates
  ○ Algal stoichiometry
  ○ Detrital dissolution and settling
  ○ Hydrolysis
  ○ Reaeration coefficient or formulation</td><td>• Submodels (sediment diagenesis, filter feeding benthos, toxicants, SAV, carbonate cycle)
• ICM kinetics libraries have been incorporated into the Adaptive Hydrodynamics (ADH) Model. ADH is a state-of-the art model that operates on an unstructured mesh of (usually) triangular elements. The unstructured mesh and triangular elements provide optimal resolution in systems of complex geometry. The adaptive mesh and ADH features such as wetting and drying of shallow regions are now available to ICM.
• Used for Chesapeake Bay TMDL</td></tr>
</table>

Model Fact Sheet

Model Name:	Deltares Water Quality (DELWAQ)/D – Water Quality/D-Ecology
Developer:	Deltares
Current Version:	Delft3D version 4.01.00.rc.09
Contact:	https://oss.deltares.nl/web/delft3d/delwaq1/-/message_boards/category/205375

Model Description	DELWAQ is the engine of the D-Water Quality and D-Ecology programs of the Delft3D suite. It is based on a rich library from which relevant substances and processes can be selected to quickly put water and sediment quality models together. The processes library covers many aspects of water quality and ecology, from basic tracers, dissolved oxygen, nutrients, organic matter, inorganic suspended matter, heavy metals, bacteria and organic micro-pollutants, to complex algae and macrophyte dynamics. High performance solvers enable the simulation of long periods, often required to capture the full cycles of the processes being modeled. The finite volume approach underlying DELWAQ allows it to be coupled to both the structured grid hydrodynamics of the current Delft3D-FLOW engine and the upcoming D-Flow Flexible Mesh engine (1D-2D-3D) of the Delft3D Flexible Mesh Suite (or even other models such as TELEMAC). Currently, the full source code is available for Delft3D-FLOW (including morphology), Delft3D-WAVE, DELWAQ (D-Water Quality and D-Ecology) and PART (D-Particle Tracking) engines under GPLv3 conditions. Code revisions, knowledge updates and new features can be shared by registering with Deltares.
Model Availability	☒ Public Doman w/ Source ☐ Public Domain w/o Source
State-variables	Modules allow for various combinations including tracers, bacteria, pH, nutrients, phytoplankton, grazers, particulate and dissolved organic matter, DO, BOD, COD, inorganic matter, heavy metals, micro pollutants

Model Input Data Needs	Model Features

• Hydrodynamic information from hydrodynamic model (temperature, salinity, water elevation, flows, dispersion)
• Loading (point sources, non-point sources, rivers, atmospheric deposition)
• Boundary conditions
• Time-variable functions (fraction of daylight, solar radiation, etc.)
• Coefficients/constants for model kinetics
  ○ Plant photosynthesis and respiration
  ○ Nitrification, denitrification
  ○ Fast and slow CBOD decay rates
  ○ Algal stoichiometry
  ○ Detrital dissolution and settling
  ○ Hydrolysis
  ○ Reaeration coefficient or formulation
  ○ Sediment rates
	• Can run in parallel on multiple processors
	• Preprocessing tools available
	• Post-processing tools may be available soon
	• Can run on curvilinear, unstructured and hybrid grids.
	• Sigma layer and z-level vertical segmentation
	• Grid aggregation tool
	• Coupled to sediment flux model
	• D-Water Quality module for basic eutrophication
	• D-Ecology module for advanced multiple phytoplankton group modeling
	• GUI available for Linux and Windows environments

Model Fact Sheet

Model Name:	Environmental Fluid Dynamics Code (EFDC)
Developer:	The original development of the internally linked EFDC water quality module was led by Dr. Keyong Park at VIMS in 1995. Dr. Park, working in collaboration with Dr. Carl Cerco of the U.S. Army Corps of Engineers Research and Development Center (ERDC) adopted the CEQUAL-ICM eutrophication kinetic formulation and sediment flux model into the EFDC code.
Current Version:	1.01 (September 2007)
Contact:	https://www.epa.gov/ceam/environment-fluid-dynamics-code-efdc-download-page

<table>
<tr><td>Model Description</td><td colspan="2">The Environmental Fluid Dynamics Code (EFDC) is a multifunctional surface water modeling system, which includes hydrodynamic, sediment-contaminant, and eutrophication components. EFDC has been applied to over 100 water bodies including rivers, lakes, reservoirs, wetlands, estuaries, and coastal ocean regions in support of environmental assessment and management and regulatory requirements.

Although coupled hydrodynamic and water quality modeling efforts had traditionally used separate externally linked models, such as DYNHYD or EFDC and WASP and CH3D-WES and CE-QUAL-ICM, the alternative of a transparent, internally linked hydrodynamic and water quality modeling was adopted along with the CE-QUAL-ICM formulation for implementation in EFDC. The original notation used in CE-QUAL-ICM (Cerco and Cole, 1995) including the sediment diagenesis model (DiToro and Fitzpatrick, 1993) has been retained.

Three versions of the EFDC model are available: (1) EFDCepa; (2) SNL-EFDC; and (3) EFDC+.

Applications: Peconic Estuary (Tetra Tech, 2000, 2005); Norwalk Harbor (Tetra Tech, 1995); and the Delaware River Estuary (Philadelphia Water Department, 2015). Embayment models of hydrodynamics for the North Shore of Long Island in support of the NYS DEC Long Island Nitrogen Action Plan (LINAP) (Wilson, 2018).</td></tr>
<tr><td>Model Availability</td><td colspan="2">☐ Public Doman w/ Source ☒ Public Domain w/o Source (EFDCepa, EFDC+)</td></tr>
<tr><td>State-variables</td><td colspan="2">DO, Org-C, NH4-N, NO23-N, ON, TN, SRP, OP, TP, BSi, NBSi, ISS, PHYTT, PHYTG, ALGBT, ALGBG, ZOO, SAV, TEMP, SAL, Macrophytes</td></tr>
<tr><td colspan="2">Model Input Data Needs</td><td>Model Features</td></tr>
</table>

• All hydrodynamic inputs described on EFDC hydrodynamic model fact sheet
• Loads (point sources, non-point sources, rivers, atmospheric)
• Kinetic coefficients for
  o Plant photosynthesis and respiration
  o Nitrification, denitrification
  o Fast and slow CBOD decay rates
  o Algal stoichiometry
  o Detrital dissolution and settling
  o Hydrolysis
  o Reaeration coefficient or formulation
	• Submodels (Sediment diagenesis, filter feeding benthos, toxicants, SAV, carbonate cycle)
	• Runs simultaneously with the hydrodynamic model
	
	References:
	
	Tetra Tech. 2000. Three-dimensional Hydrodynamic and Water Quality Model of Peconic Estuary, Draft Final Report. Prepared for Peconic Estuary Program, County of Suffolk, Department of Health Services, Office of Ecology, Riverhead, NY. Prepared by Tetra Tech, Inc., Fairfax, VA. June 2000.
	
	Philadelphia Water Dept. 2015. Tidal Waters Water Quality Model- Bacteria and Dissolved Oxygen. Consent Order & Agreement Deliverable IX and X. City of Philadelphia Combined Sewer Overflow Long Term Control Plan Update, Philadelphia Water Department, Philadelphia, PA.
	
	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. Prepared by Tetra Tech, Inc., Fairfax, VA.
	
	Tetra Tech. 2005. Refinements to the Three-dimensional Hydrodynamic and Water Quality Model of Peconic Estuary, Draft Report. Prepared for Peconic Estuary Program, County of Suffolk, Department of Health Services, Office of Ecology, Riverhead, NY. Prepared by Tetra Tech, Inc., Fairfax, VA. March 2005.
	
	Wilson, R.E. 2018. Quality Assurance Project Plan for EFDC and FVCOM Modeling for Nassau County Long Island Embayments, prepared for NYSDEC.

Model Fact Sheet

Model Name:	SNL-Environmental Fluid Dynamics Code (SNL-EFDC)
Developer:	Sandia National Laboratories
Current Version:	2008 GNU General Public License version 2.0 (GPLv2)
Contact:	https://sourceforge.net/projects/snl-efdc/

<table>
<tr><td>Model Description</td><td colspan="2">Sandia National Laboratories' (SNL) environmental assessment modeling tool helps optimize the design of MHK-turbine array layouts within ocean, tidal, and river systems to balance energy generation efficiency with environmental considerations. The new tool, SNL-EFDC, is an augmented version of US EPA's Environmental Fluid Dynamics Code (EFDC) and includes; (1) a new module that simulates energy conversion (momentum withdrawal) by MHK turbine-like devices including commensurate changes in the turbulent kinetic energy and turbulent kinetic energy dissipation rate, (2) new, advanced sediment dynamics routines, and (3) augmented water quality modules. SNL-EFDC has been verified and validated against flume measurements of flow around sub-scale turbines and actuator disks.</td></tr>
<tr><td>Model Availability</td><td colspan="2">☒ Public Doman w/ Source ☐ Public Domain w/o Source</td></tr>
<tr><td>State-variables</td><td colspan="2">DO, Org-C, NH4-N, NO23-N, ON, TN, SRP, OP, TP, BSi, NBSi, ISS, PHYTT, PHYTG, ALGBT, ALGBG, ZOO, SAV, TEMP, SAL, Macroalgae</td></tr>
<tr><td colspan="2">Model Input Data Needs</td><td>Model Features</td></tr>
<tr><td colspan="2">• All hydrodynamic inputs described on SNL-EFDC hydrodynamic model fact sheet
• Loads (point sources, non-point sources, rivers, atmospheric)
• Kinetic coefficients for
  ○ Plant photosynthesis and respiration
  ○ Nitrification, denitrification
  ○ Fast and slow Org-C decay rates
  ○ Algal stoichiometry
  ○ Detrital dissolution and settling
  ○ Hydrolysis
 ○ Aeration coefficient (or formulation type)</td><td>• Submodels (Sediment diagenesis, filter feeding benthos, toxicants, SAV, carbonate cycle)
• Runs simultaneously with the hydrodynamic model
  • The model uses the same code for water quality as EPA-EFDC with the addition of pH effects on algal growth limitation. The pH code modifications are documented in SNL-EFDC: pH Effects User Manual (SNL, 2012), where it is noted that the original EFDC hydrodynamic model manuals (Hamrick, 2007a,b) and water quality manuals (Cerco and Cole, 1995) should be used for documentation.

References:

Hamrick, J.M., 2007a. The Environmental Fluid Dynamics Code: User Manual, I. Tetra Tech, Editor, US EPA: Fairfax, VA.

Hamrick, J.M., 2007b. The Environmental Fluid Dynamics Code: Theory and Computation, I. Tetra Tech, Editor, US EPA: Fairfax, VA.

Cerco, C.F. and T. Cole, 1995. User's Guide to the CE-QUAL-ICM Three-Dimensional Eutrophication</td></tr>
</table>

	Model, Release Version 1.0, U.S. Army Corps of Engineers, ERDC, Vicksburg, MS.

Model Fact Sheet

Model Name:	Row Column AESOP (RCA)
Developer:	HDR
Current Version:	v3.0
Contact:	https://www.hdrinc.com/services/environmental-sciences/water-quality-hydrodynamic-modeling-software

Model Description	RCA (Row Column Advance Ecological Systems mOdeling Program, AESOP) is a generalized water quality/ecosystem model, built on the WASP framework (originally developed by HDR modeling staff) that is capable of being linked to the ECOMSED, EFDC and ROMS hydrodynamic models. The RCA model includes pathogen kinetics; full eutrophication kinetics to model nutrients, algae, light and dissolved oxygen including a sediment flux model that calculates sediment nutrient fluxes and sediment oxygen demand as a function of settled organic matter. The RCA model is routinely used for complex nutrient (eutrophication) assessments and CSO/SSO pathogen fate and transport studies in estuaries, rivers and lakes. Applications: See Attachment 3.
Model Availability	☒ Public Doman w/ Source ☐ Public Domain w/o Source
State-variables	Salinity, DOP, POP, PO4-P, DON, PON, NH3-N, NO23-N, BSi, DSi, DOC, POC, DO, Multiple phytoplankton groups

Model Input Data Needs	Model Features

• Hydrodynamic information from hydrodynamic model (temperature, salinity, water elevation, flows, dispersion)
• Loading (point sources, non-point sources, rivers, atmospheric deposition)
• Boundary conditions
• Time-variable functions (fraction of daylight, solar radiation, etc.)
• Coefficients/constants for model kinetics
  o Plant photosynthesis and respiration
  o Nitrification, denitrification
  o Fast and slow CBOD decay rates
  o Algal stoichiometry
  o Detrital dissolution and settling
  o Hydrolysis
  o Reaeration coefficient or formulation type
  o Sediment Flux Model rates
	• Multiple integration schemes
	• Coupled to Sediment Flux Model (SFM)
	• Benthic algae, macroalgae and bivalve subroutines available
	• Open source allows for code modifications to add new features
	• Has been applied to the Long Island Sound

Model Fact Sheet

Model Name:	Unstructured Grid - Row Column AESOP (UG-RCA)
Developer:	University of Massachusetts-Dartmouth and Woods Hole Oceanographic Institute
Current Version:	3.1.6
Contact:	http://fvcom.smast.umassd.edu/fvcom/

Model Description	UG-RCA is an unstructured grid version of RCA (Row Column Advance Ecological Systems mOdeling Program, AESOP). UG-RCA is a generalized water quality/ecosystem model, built on the WASP framework (originally developed by HDR modeling staff) that is capable of being linked to the FVCOM hydrodynamic model. The UG-RCA model includes pathogen kinetics; full eutrophication kinetics to model nutrients, algae, light and dissolved oxygen including a sediment flux model that calculates sediment nutrient fluxes and sediment oxygen demand as a function of settled organic matter.
Model Availability	☒ Public Doman w/ Source ☐ Public Domain w/o Source
State-variables	Salinity, DOP, POP, PO4-P, DON, PON, NH3-N, NO23-N, BSi, DSi, DOC, POC, DO, Multiple phytoplankton groups

Model Input Data Needs	Model Features

• Hydrodynamic information from hydrodynamic model (temperature, salinity, water elevation, flows, dispersion)
• Loading (point sources, non-point sources, rivers, atmospheric deposition)
• Boundary conditions
• Time-variable functions (fraction of daylight, solar radiation, etc.)
• Coefficients/constants for model kinetics
  ○ Plant photosynthesis and respiration
  ○ Nitrification, denitrification
  ○ Fast and slow CBOD decay rates
  ○ Algal stoichiometry
  ○ Detrital dissolution and settling
  ○ Hydrolysis
  ○ Reaeration coefficient or formulation
  ○ Sediment rates
	• Multiple integration schemes
	• Coupled to Sediment Flux Model (SFM)
	• Open source allows for code modifications to add new features
	• MPI parallelization
	
	• Permission may be required for use in commercial settings.

Model Fact Sheet

Model Name:	Water Quality Analysis Simulation Program (WASP8)
Developer:	Robert B. Ambrose, Jr. (retired) and Tim A. Wool. U.S. EPA ORD/NERL-ERD; James L. Martin, Mississippi State University
Current Version:	v8.32
Contact:	Tim Wool (wool.tim@epa.gov) https://www.epa.gov/ceam/wasp8-download

Model Description	The Water Quality Analysis Simulation Program (WASP) is an enhancement of the original WASP (Di Toro et al., 1983; Connolly and Winfield, 1984; Ambrose, R.B. et al., 1988). This model helps users interpret and predict water quality responses to natural phenomena and man-made pollution for various pollution management decisions. WASP is a dynamic compartment-modeling program for aquatic systems, including both the water column and the underlying benthos. WASP allows the user to investigate 1, 2, and 3 dimensional systems, and a variety of pollutant types. The state variables for the given modules are given in the table below. The time varying processes of advection, dispersion, point and diffuse mass loading and boundary exchange are represented in the model. WASP also can be linked with hydrodynamic and sediment transport models that can provide flows, depths velocities, temperature, salinity and sediment fluxes. This release of WASP includes the sediment diagenesis model linked to the Advanced Eutrophication sub model, which predicts sediment oxygen demand and nutrient fluxes from the underlying sediments. Note on code availability from Wool et al. (2020): “Section 2.5.3: Because of the multiple contributors to the development of the user interface and scientific models, all WASP source code is stored in a Git repository (an open source distributed version control system) and is integrated with an automated continuous-integration/continuous-delivery (CI/CD) system. The CI/CD system automatically builds and tests every new WASP source code revision, which helps to maintain high quality WASP software, as well as providing full traceability of all WASP release artifacts. The authors of WASP do not post the WASP source code to the general public; this is done to maintain the integrity of the model. All underlying equations used in the model are documented in users’ manuals or workshop materials. The WASP developers have always worked with the user community to make enhancements to the modeling framework.” “Section 4: Initially and through WASP5, the source code was distributed with WASP. However, as WASP evolved the code and internal linkages became more complex, the distribution of the source code was limited to model developers. That trend seems common today” (Wool et al., 2020).
Model Availability	☐ Public Doman w/ Source ☒ Public Domain w/o Source Contact developers
State-variables	NH3-N, NO3-N, DON, SRP, DOP, DSi, DSi, CBOD, DO, Detrital Matter (C, N, P, Si), Salinity, Benthic Algae, Periphyton, Inorganic Solids, Phytoplankton

Model Input Data Needs	Model Features

• Hydrodynamic information from hydrodynamic model (temperature, salinity, water elevation, flows, dispersion)
• Loading (point sources, non-point sources, rivers, atmospheric deposition)
• Boundary conditions
• Time-variable functions (fraction of daylight, solar radiation, etc.)
• Coefficients/constants for model kinetics
  ○ Plant photosynthesis and respiration
  ○ Nitrification, denitrification
  ○ Fast and slow CBOD decay rates
  ○ Algal stoichiometry
  ○ Detrital dissolution and settling
  ○ Hydrolysis
  ○ Reaeration coefficient or formulation
  ○ Sediment rates
	• Graphical User Interface
	• Pre-processor
	• Post-processor
	• Sediment diagenesis, pH submodels
	
	References:
	
	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

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Coupled ECOMSED and RCA Model Applications by HDR

Coupled ECOMSED and RCA Model Applications by HDR

Project / Location	Client	State
LIS Nutrient and DO TMDL Modeling	EPA, DEP	NY/CT
Jamaica Bay Eutrophication Studies	DEP	NY
East River Tributaries Model	DEP	NY
NY/NJ Harbor Nutrient and DO TMDL Modeling	EPA Region 2	NY/NJ/CT
Forge River TMDL Modeling	Town of Brookhaven	NY
Port Jefferson Harbor Modeling	Town of Port Jefferson	NY
Great Bay Estuary Modeling	Cities of Portsmouth, Rochester, Dover	NH
Massachusetts Bay Eutrophication Model	MWRA	MA
James River Chlorophyll-a Modeling	Virginia DEQ	VA
James River Overflow Modeling	HRSD	VA
James River Ammonia Study	City of Hopewell	VA
Delaware River/Estuary Eutrophication Model	DRBC	PA/NJ/DE
St. Jones, Murderkill, Leipsic, Smyrna, Blackbird, Little & Broadkill Rivers – TMDL Modeling	DNREC	DE
Tar-Pamlico Estuary Modeling	Tar-Pamlico Basin Association	NC
Brunswick Harbor Estuary DO Modeling	Georgia-Pacific	GA
Tampa Bay Estuary	Tampa Bay Estuary Program	FL
Fenholloway River/Gulf of Mexico – TMDL Modeling	Georgia-Pacific	FL
St. Andrews Bay Nutrient Modeling	Multiple Clients	FL
Escambia/Pensacola Bay Nutrient Modeling	Escambia Bay TMDL Coalition	FL
Perdido Bay WQBEL Modeling	International Paper	FL
Sabine River DO Modeling	International Paper	TX
San Joaquin River DO Modeling	CALFED	CA
Upper Mississippi River/Lake Pepin Phosphorus Modeling	MPCA	MN
Milwaukee Harbor/Lake Michigan Water Quality Modeling	MMSD	WI

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