Three-Dimensional Modeling and Medium-Term CyanoHABs Forecasting in Lake Champlain

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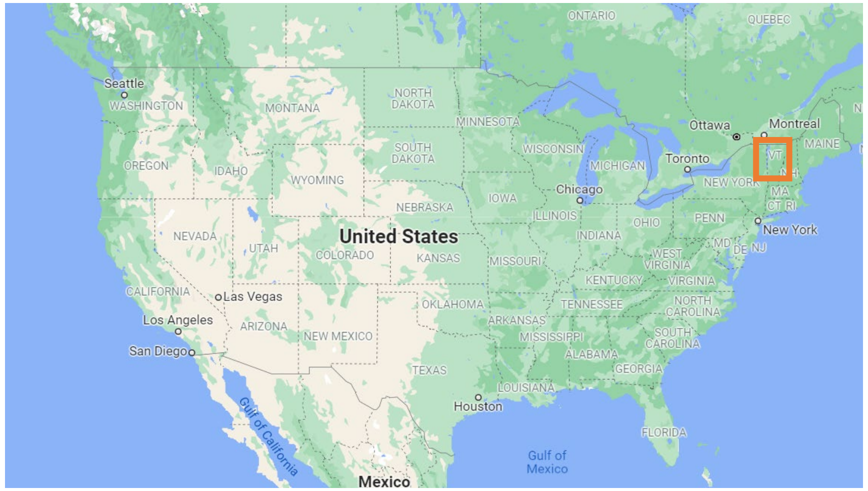
WATER QUALITY CONCERNS IN LAKE CHAMPLAIN

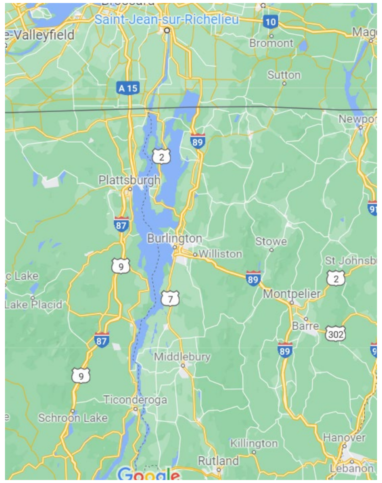
- Volume of 21 million acre-feet
- Water supply for 200,000 people
- Recreational value reliant on high water quality

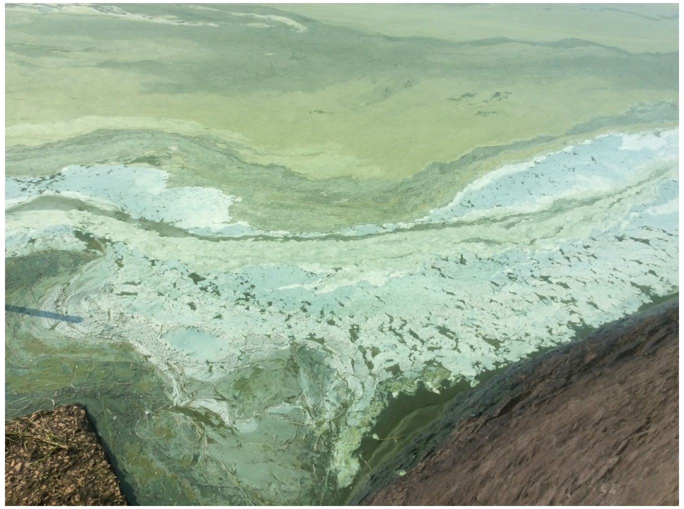
High P loading and increasing air temperature have led to eutrophication in eastern bays

Eastern Bays of Lake Champlain have experienced increasingly problematic cyanobacteria blooms

- Significant economic and recreational impacts
- Future outlook concerning as air temperatures continue to rise







Missisquoi Bay CyanoHAB August 2021
Image via Vermont Cyanobacteria Tracker

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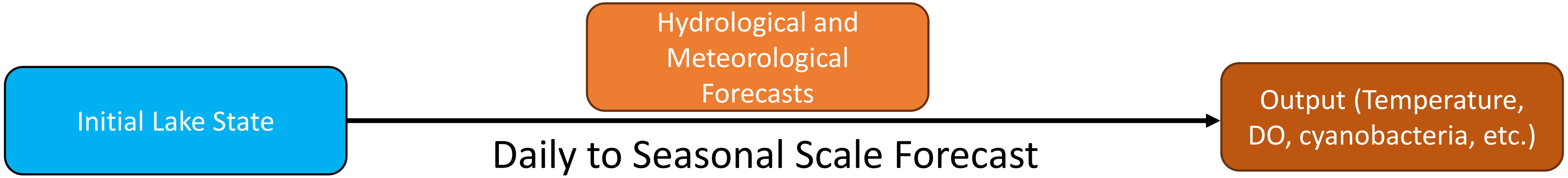
Water Quality Forecasting Objectives



Actionable CyanoHAB forecasts to stakeholders:

- Recreational users
- Drinking water agencies
- Government and public agencies

Current Objectives

- Develop forecasting workflow for short- to seasonal-scale forecasts
- Implement 3D water quality model in forecasting workflow
- Develop framework for initial results evaluation

Long-Term Objectives

- Evaluate sources of error in cyanobacteria forecasts
- Enhance forecast performance
- Refine comparison between satellite and model output

Water Quality Model Calibration

Objective:

Extend model calibration to 6.5-year period

- Incorporate more weather and water quality scenarios
- Simulate period with recent aerial monitoring data

Previous work:

- 3D water quality model of Missisquoi Bay was calibrated for years 2017-2018 (Marti et al.)
- Model was expanded to Inland Sea and calibrated for 2017-2019

Marti, C. L.; Schroth, A. W.; Zia, A.
American Geophysical Union, Fall Meeting 2019

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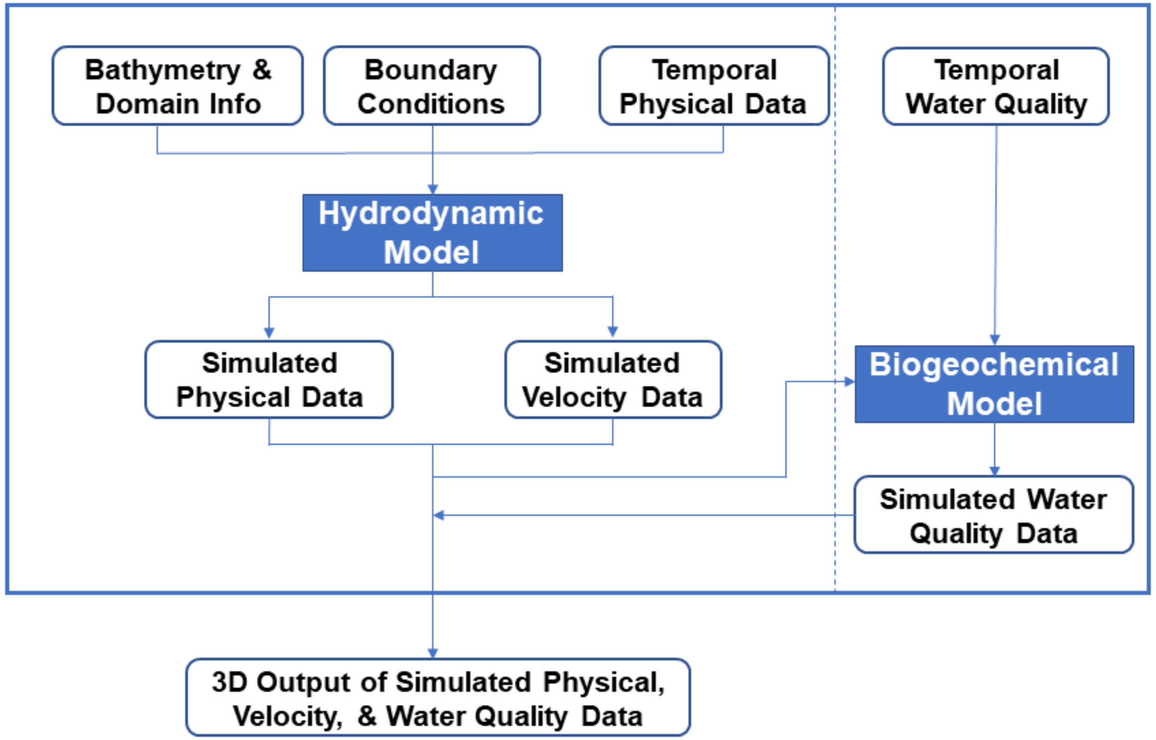
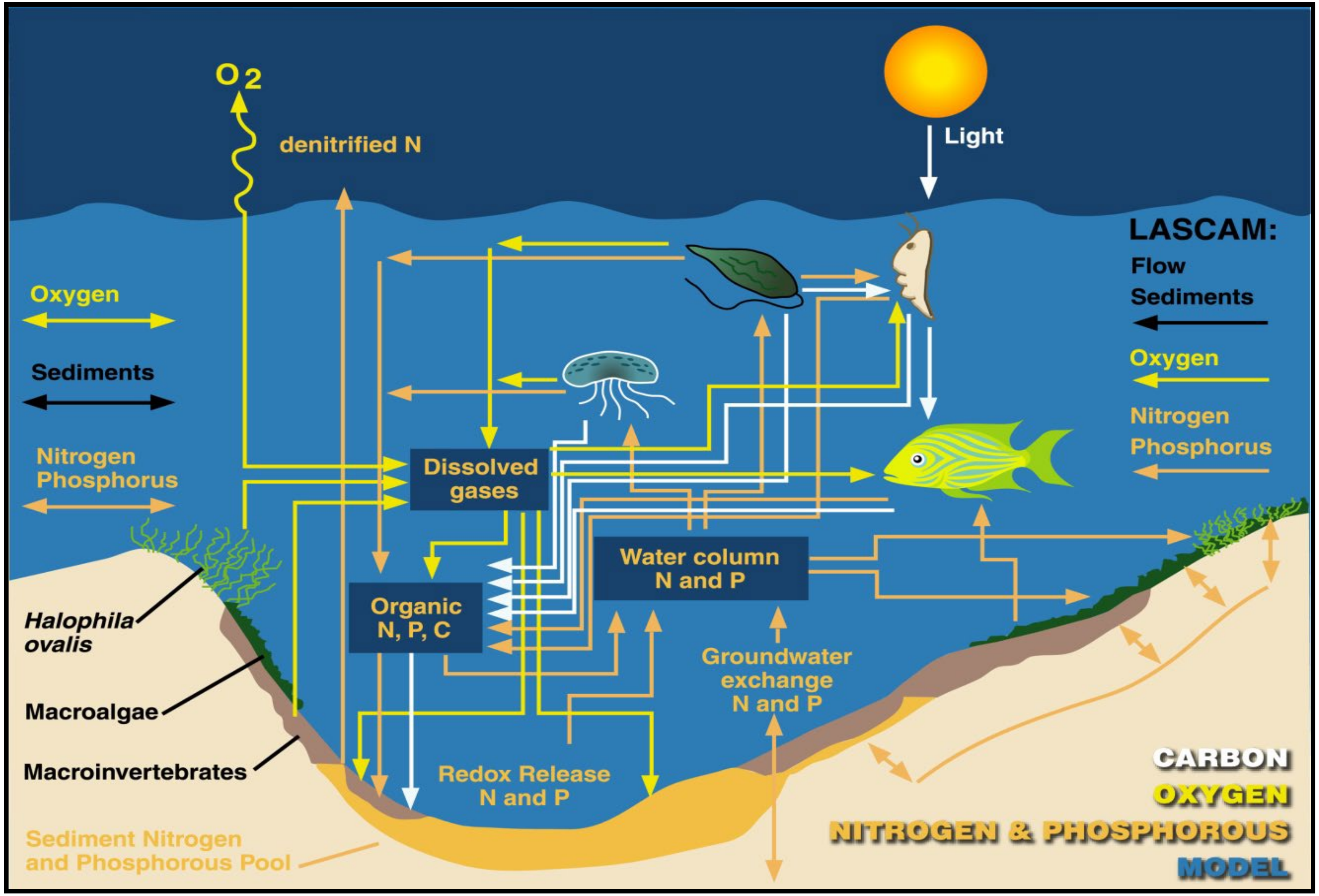
AEM3D Model Principles

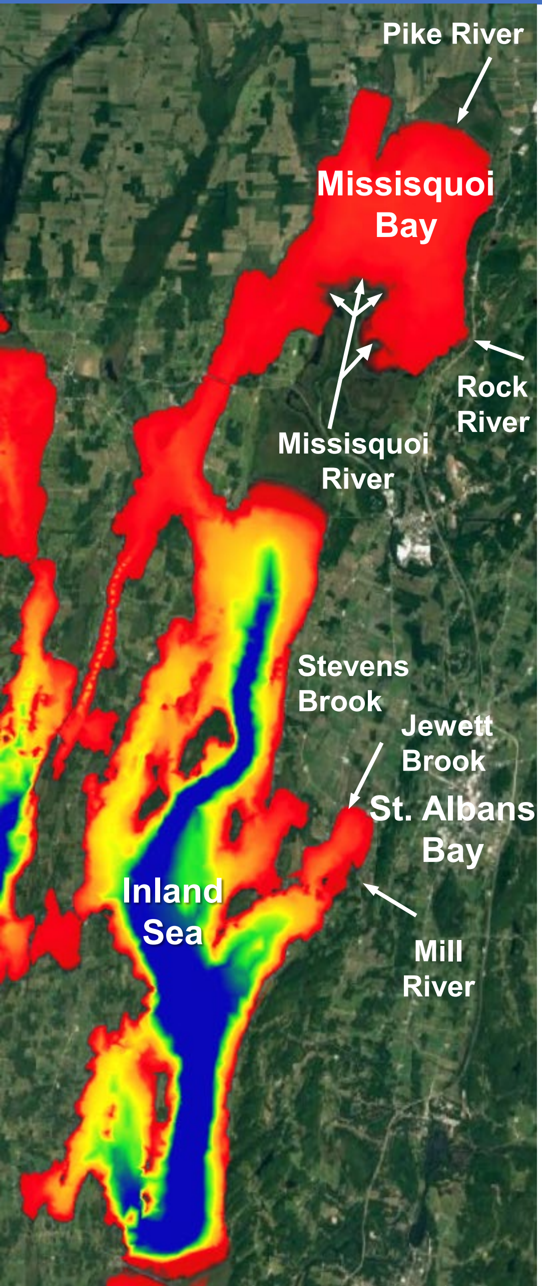
- AEM3D takes bathymetric, meteorological, and hydrological data to simulate lake hydrodynamics
- Lake hydrodynamics are coupled to biogeochemical model
- Model output parameters include:
  - Temperature
  - Dissolved oxygen concentration
  - Nutrient concentrations
  - Chlorophyll *a* concentration



AEM3D Model: Water Quality



Inland Sea (IS) Model Setup: Water Quality Model



1. Inland Sea (IS) domain defined
   - Four open boundaries defined
   - Five major inflows modeled
   - Inland Sea domain provides results for Missisquoi Bay (MB) and St. Albans Bay (SAB)
2. Implemented spatially varying parameters:
   - Air temperature
   - Solar radiation
   - Wind speed
   - Sediment oxygen demand
   - Sediment nutrient release rates
3. Modeled two phytoplankton groups:
   - Freshwater diatoms
   - Cyanobacteria
4. Extended calibration period to years 2017-2023

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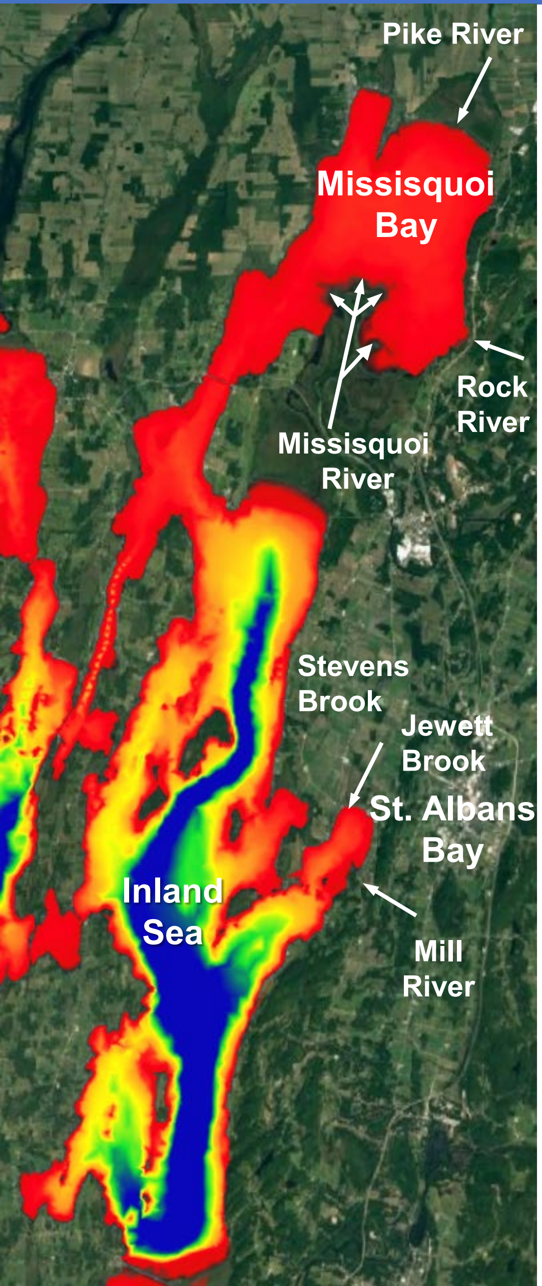
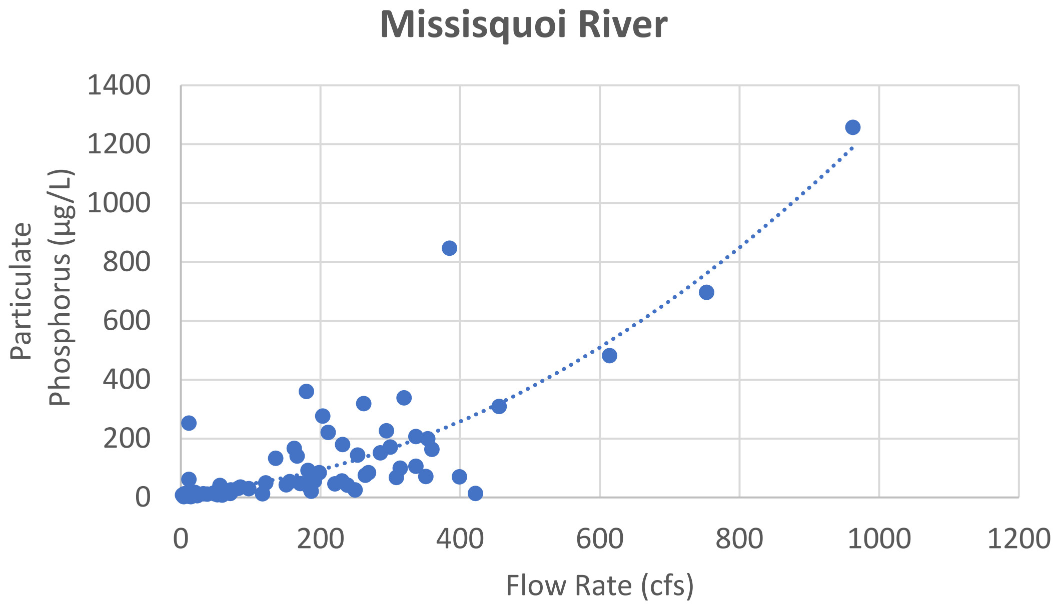
Inflows and External Loading

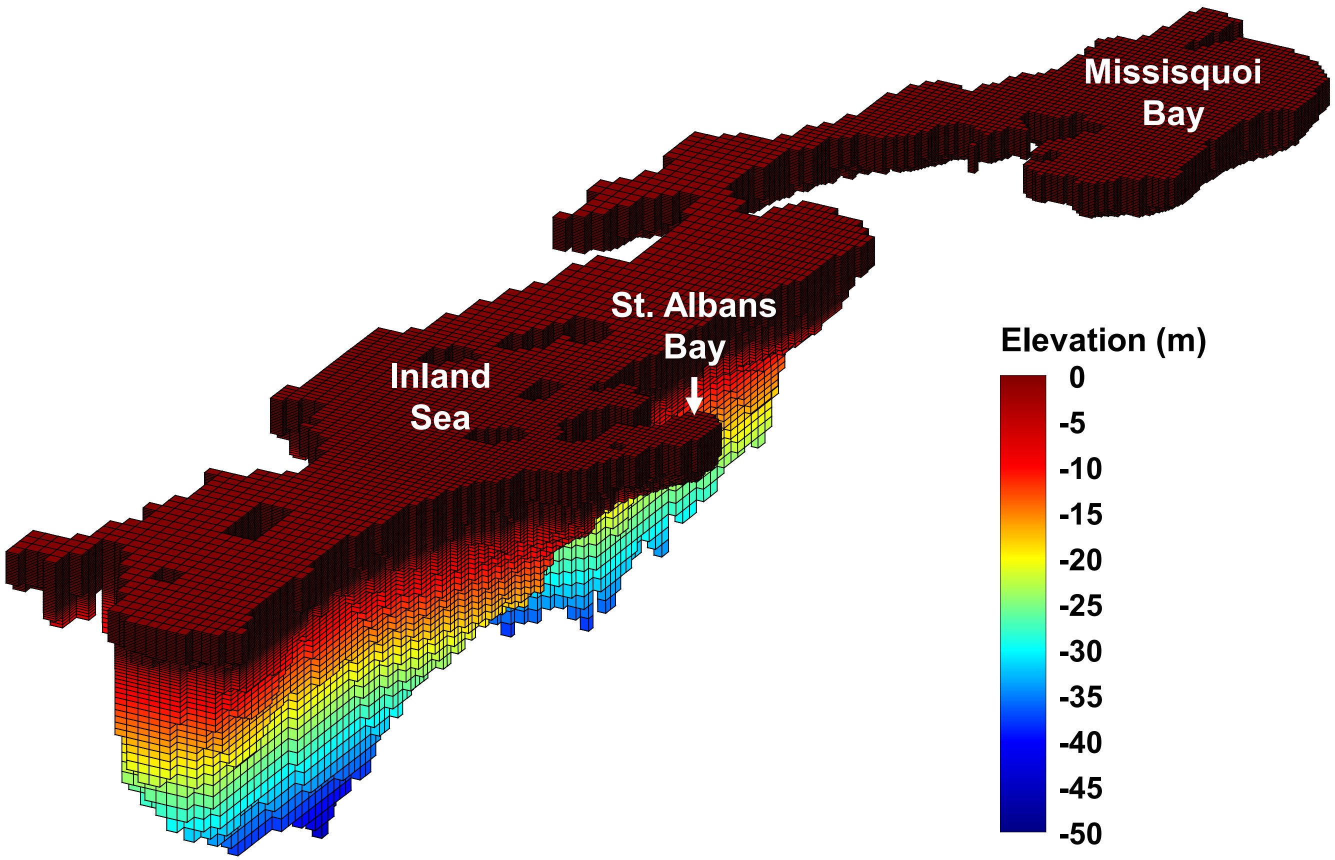


- High-frequency flow data obtained from USGS for all five inflows
- Inflow nutrient concentrations were determined base on concentration-discharge (C-Q) relationships
    - Flow rate and low-frequency nutrient data fit to determine a C-Q relationship
        - Random forest model also developed (Isles et al.)
    - C-Q relationships used to generate high-frequency nutrient input



Isles, P.D.F. *Water Research* **2024**

IS Model Setup: Grid



Horizontal Grid:

200 m x 200 m in bays

Up to 400 m x 400 m in Inland Sea

Vertical Grid:

0.25 m at surface and epilimnion

Up to 2.0 m at depth in Inland Sea

Grid stretching retains accuracy while providing run times compatible with long-term simulations

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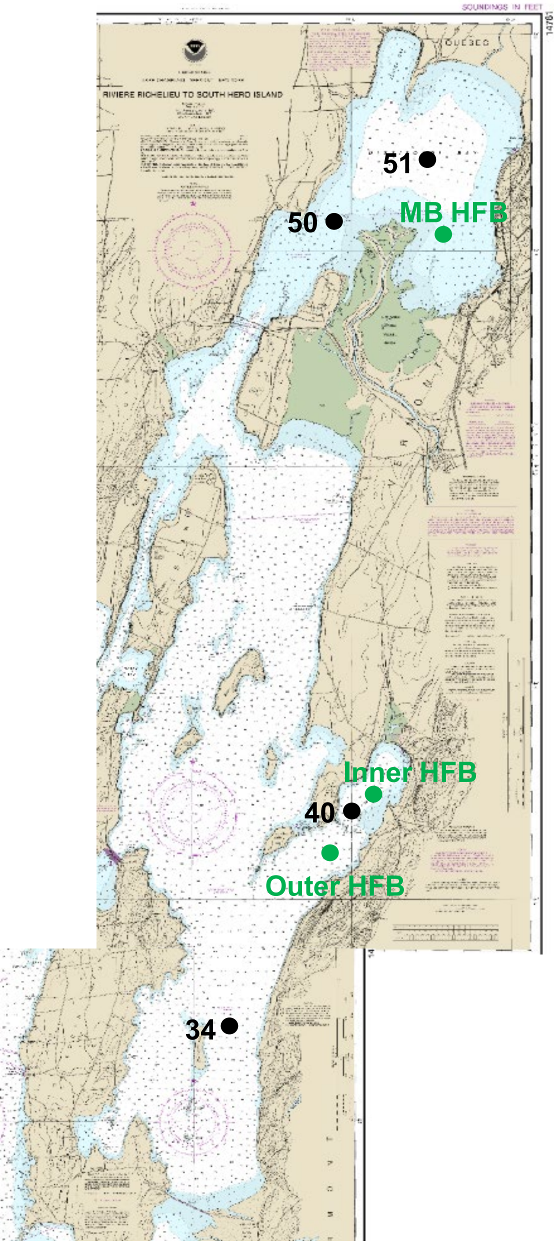
IS Model Calibration: Water Quality Model

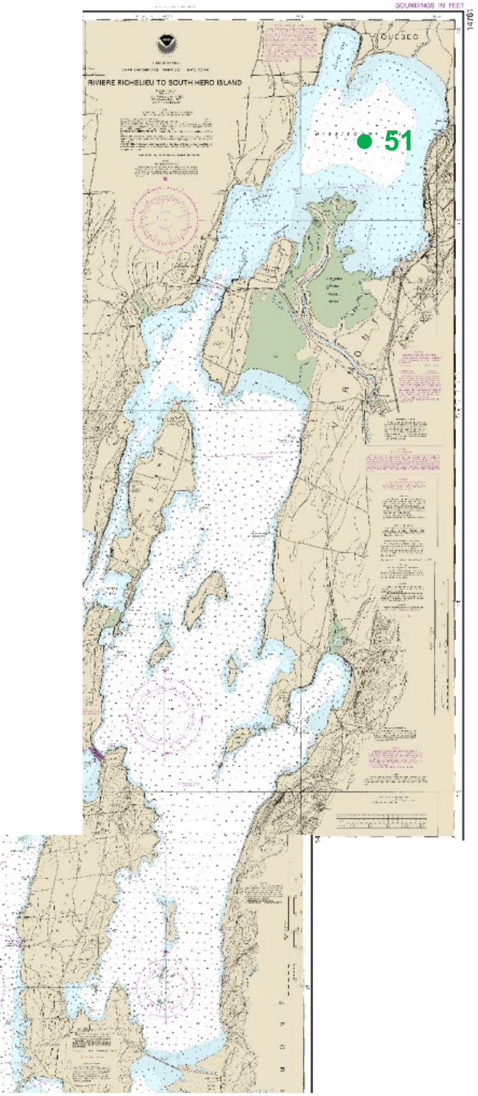


Model Calibration:

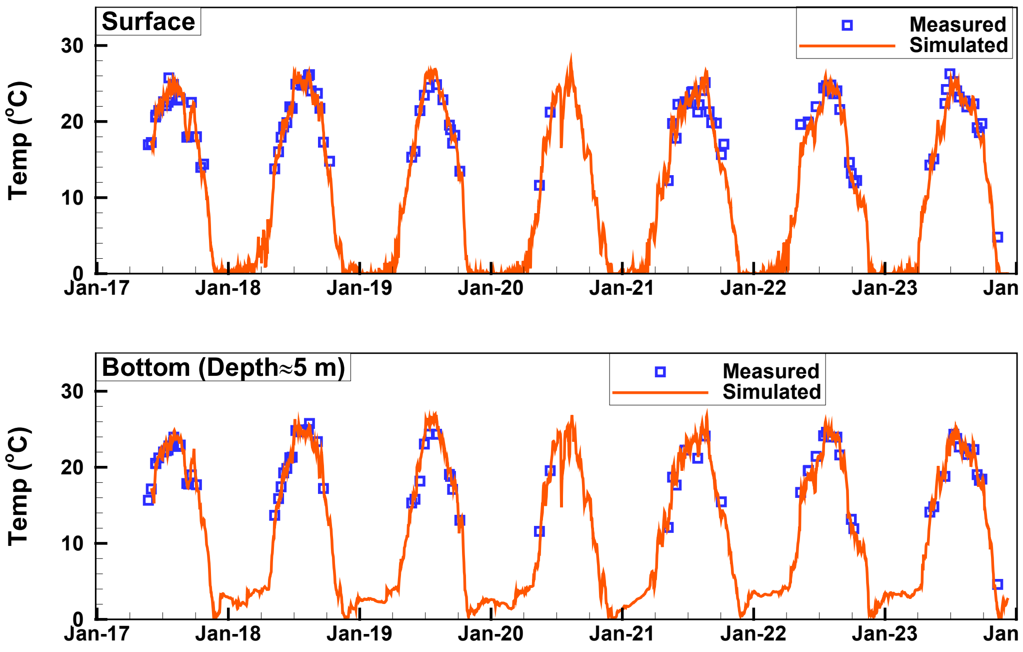
1. Adjusted ice cover parameters (better temperature comparisons in the spring)
2. Adjusted DO parameters including oxygen production and sediment oxygen demand– good agreement at all three locations
3. Improved sediment nutrient release parameters
4. Adjusted phytoplankton parameters to match growth, nutrient uptake, and chlorophyll *a* production

Water quality model calibration was based on previous Missisquoi Bay model calibration (Marti et al.) and 2017-2019 calibration

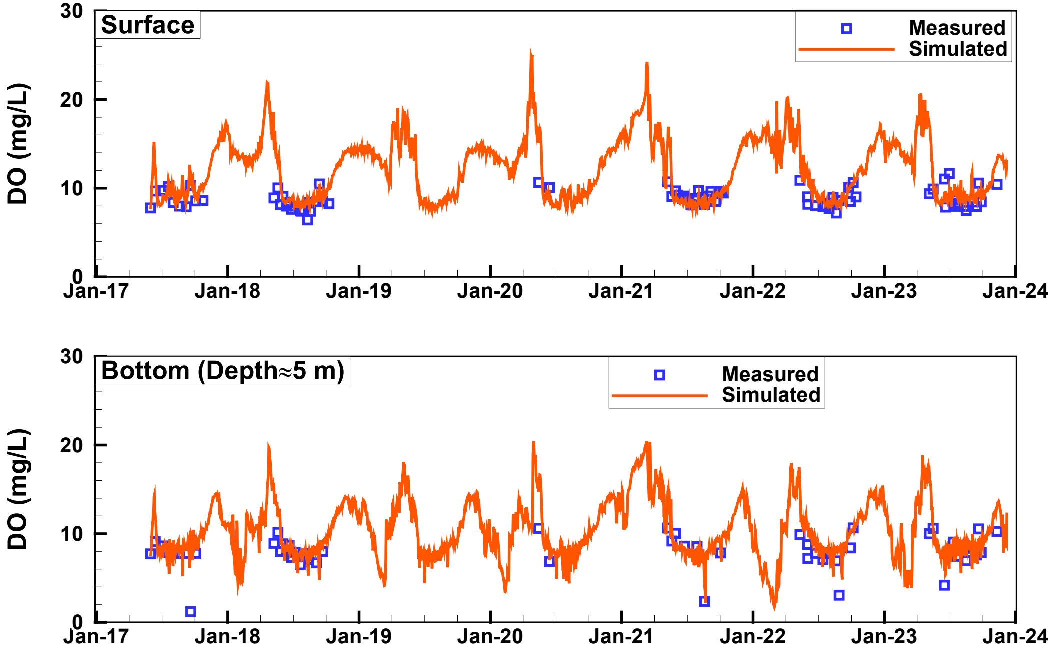
Temperature and DO Comparison



Temperature

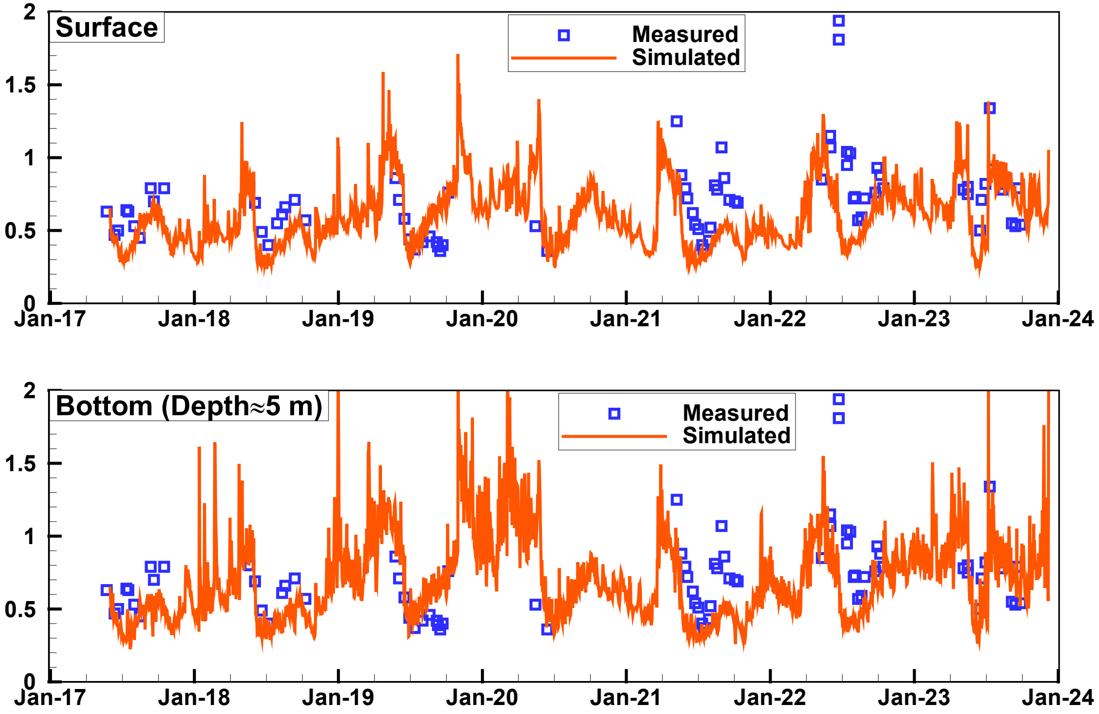


Dissolved Oxygen

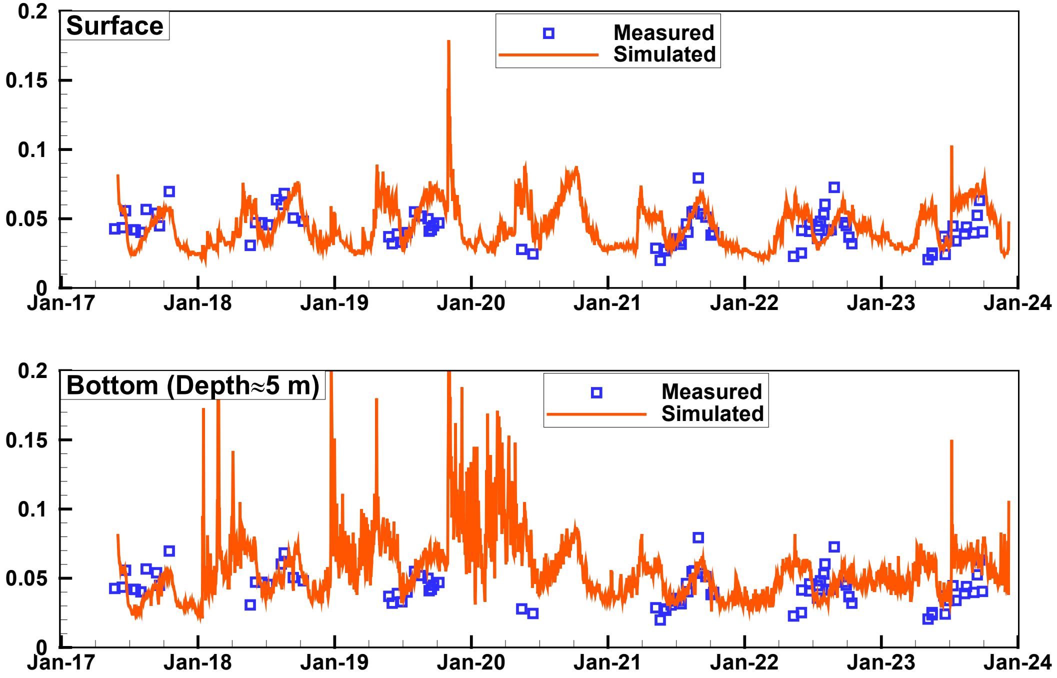


TN, TP Comparison

Total Nitrogen



Total Phosphorus



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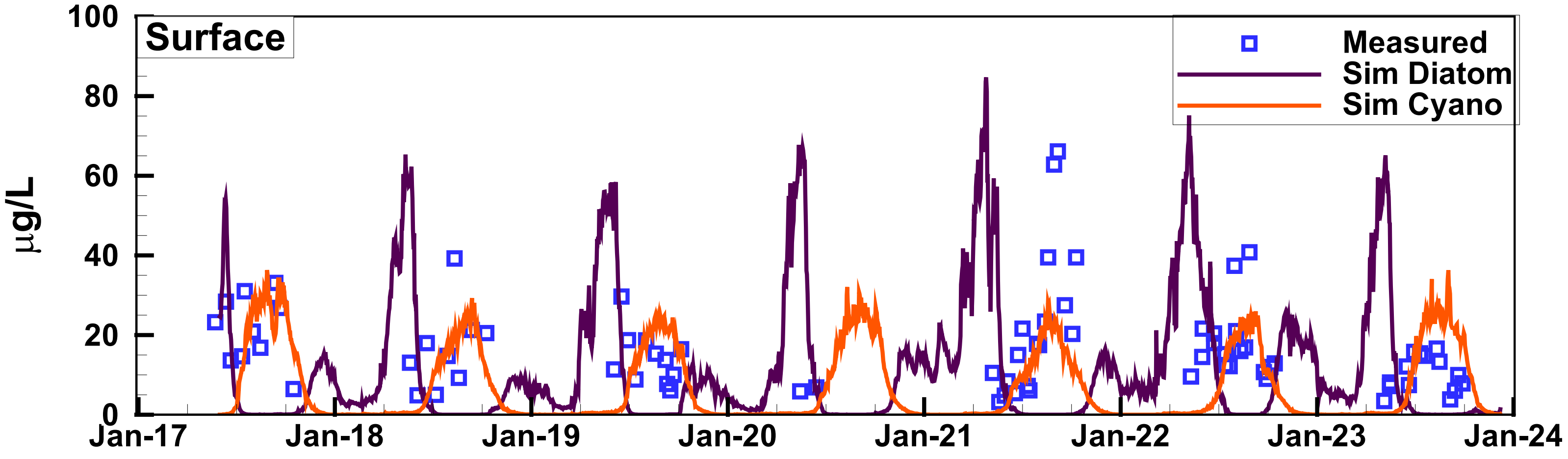
CHLa Comparison and Statistics

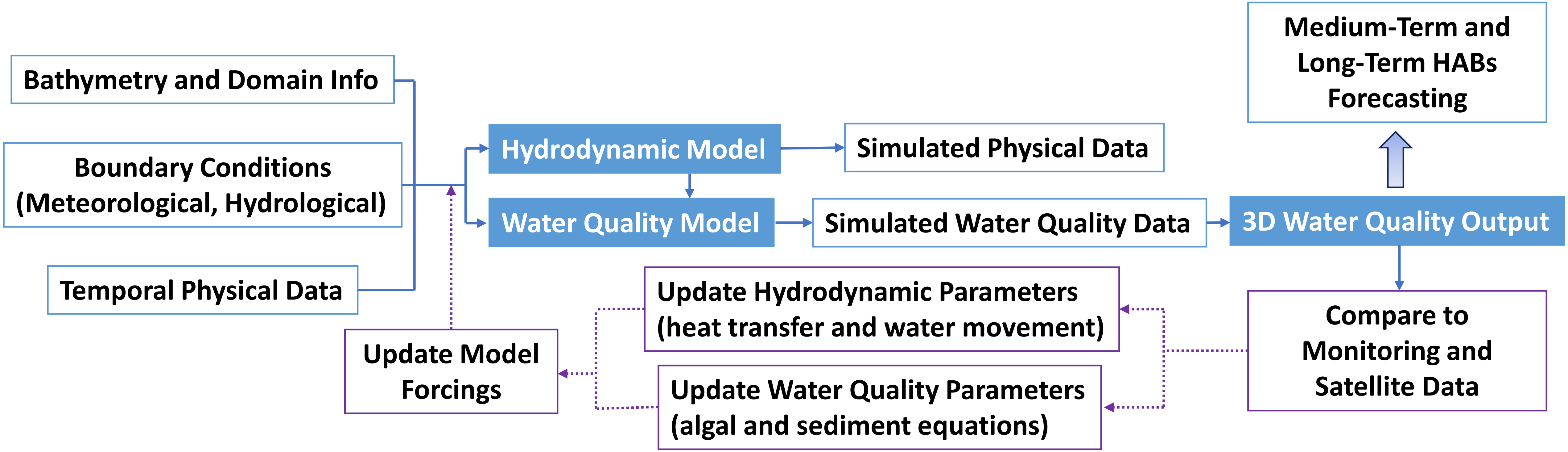


Model Statistics: Mean Error (RME)

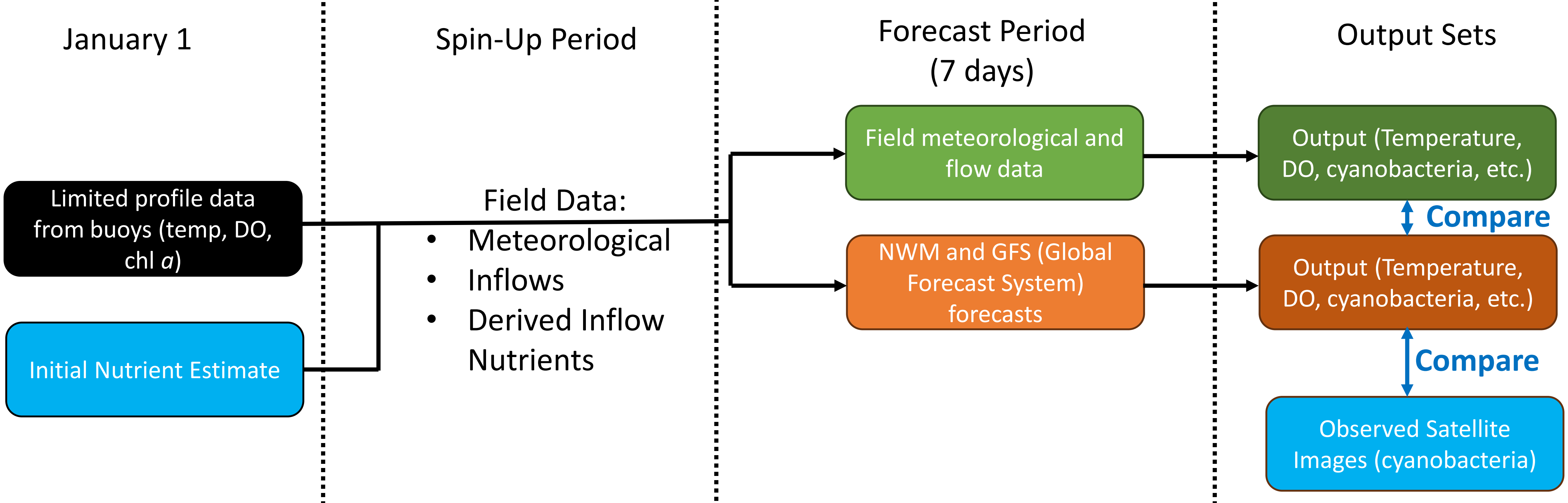
	MB	SAB	IS
Station	51	40	34
Temp (°C)	1.43 (6.6%)	1.06 (4.7%)	0.41 (1.9%)
DO (mg/L)	-1.03 (9.9%)	-0.28 (-2.1%)	0.19 (1.2%)
TN (mg/L)	0.14 (8.8%)	0.05 (8.1%)	0.00 (-0.6%)
TP (mg/L)	-0.008 (-13.3%)	0.002 (3.9%)	0.000 (0.4%)
Chl *a* (μg/L)	-2.75 (-2.5%)	2.95 (5.6%)	-2.52 (-8.6%)

$$^{ǂ}Relative\ ME\ (\%) = \frac{ME * 100}{(Max_{obs} - Min_{obs})}$$

Forecasting Workflow



Medium-Term Forecasting



Compare Results:

- Bloom Incidence
- Bloom Duration

Medium-Term Forecast Inputs

Startup (January 1st of forecast year)

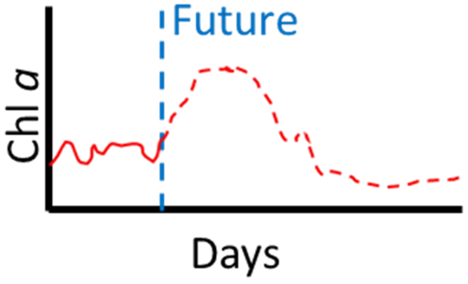
- Most recent lake profile data (temperature, DO, nutrients, etc.)
- Ice cover

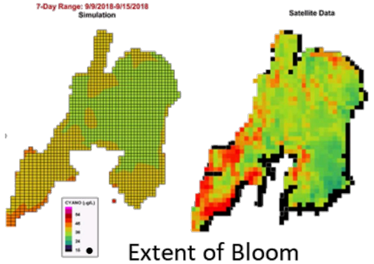
Spin-up period (January 1st to forecast run date)

- Historical weather data
- Adjusted gauged inflow data
- Historical lake level
- Inflow nutrients from CQ equations

Forecast period (7 days)

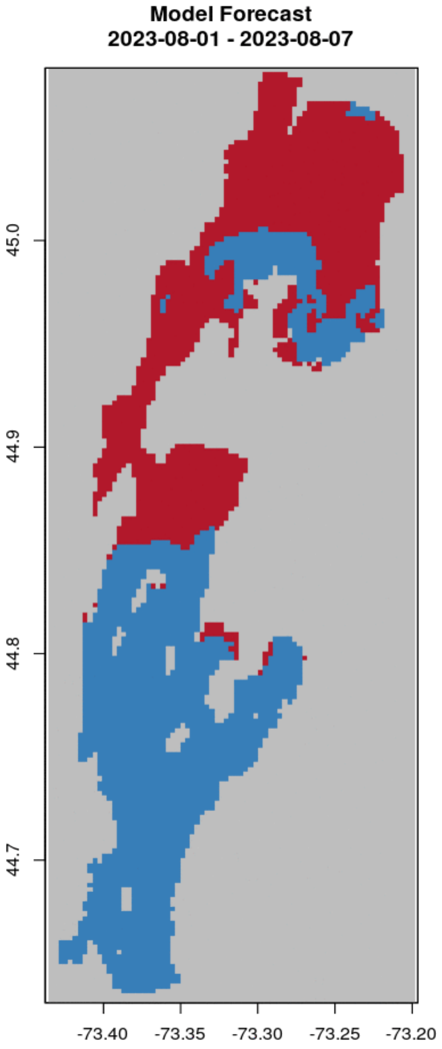
- GFS 10-day forecast
- NWM streamflow forecast
    - Inflows from CQ equations

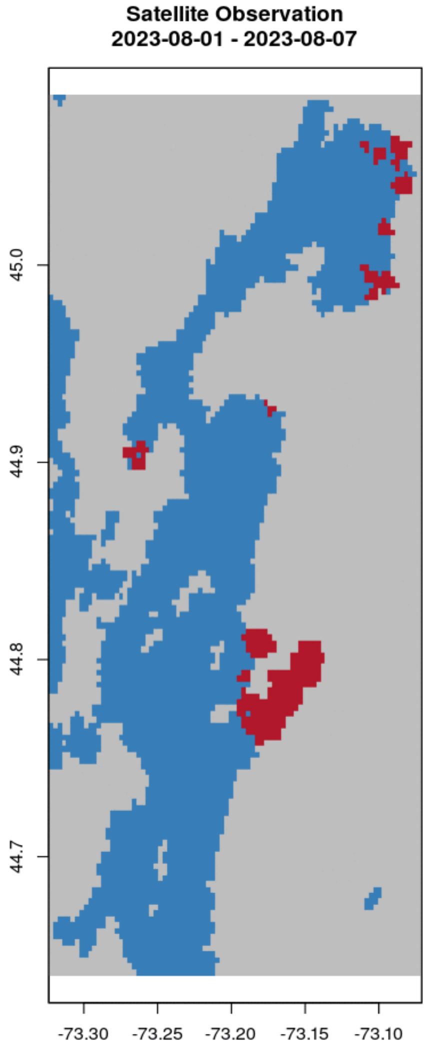




Extent of Bloom
- Duration of Bloom
- Intensity of Bloom

Medium-Term Forecast Results



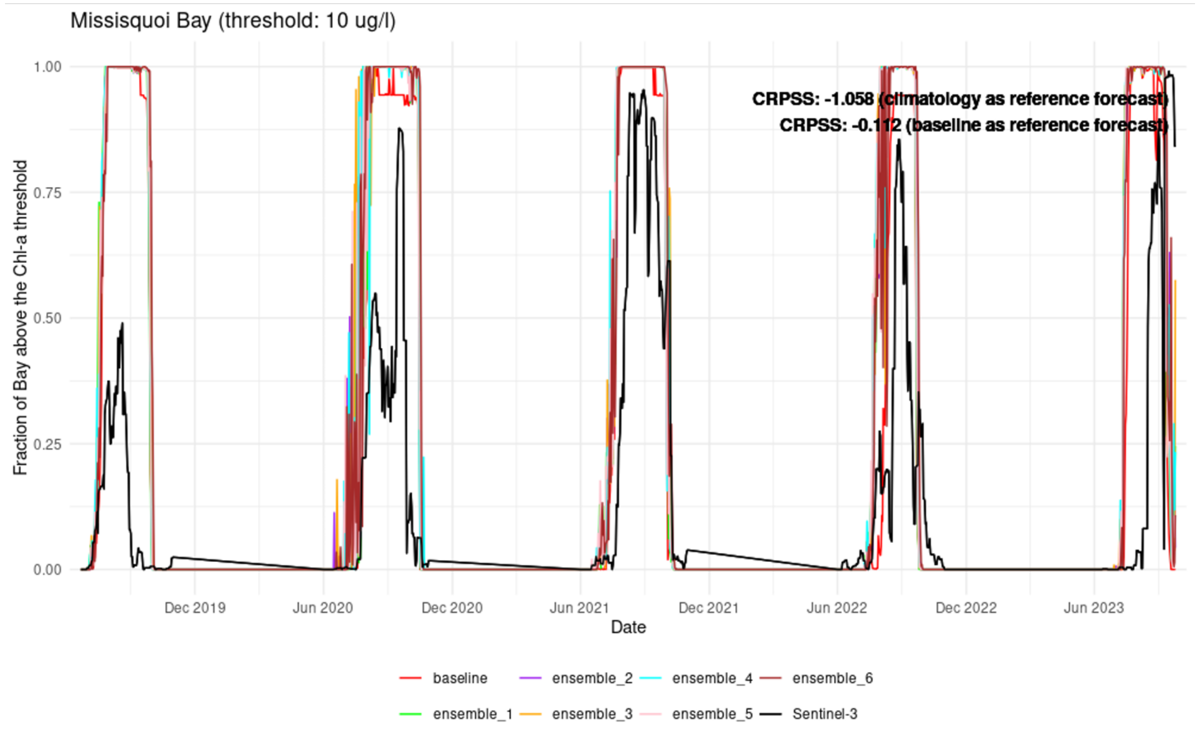


cHABs Free
[Chl-a >= 12.5 µg/l]

cHABs
[Chl-a >= 12.5 µg/l]

cHABs Free
[CI_{cyano} < 0.000085]

cHABs
[CI_{cyano} >= 0.000085]



Model generated weekly HABs forecasts are compared against Sentinel 3 derived Cyanobacteria Index (CI)

Forecast Enhancements and Sensitivity Analysis

Enhancements and Ongoing Challenges

- Data assimilation and reduction of spin-up period
- Processing of satellite data
  - Satellite may fail to detect blooms
    - Many data gaps due to cloud cover and low data frequency
    - Some blooms detected by fluorescent sensors but not satellite

Sensitivity Analyses: Understand contribution of various input factors to error

- Perform forecast runs with varying:
  - Initial conditions
  - Flows and nutrient loadings
  - Weather forecasts: individual parameters
- Determine statistical dependence of forecast on each input

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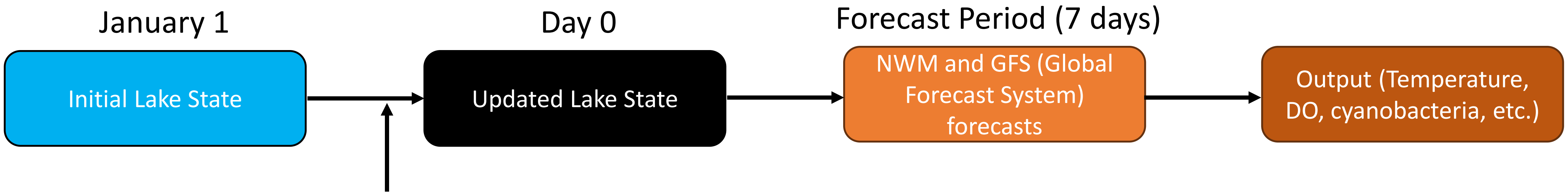
Data Assimilation

Enhancement of startup conditions

- AEM3D model can stabilize with short (e.g., 1-week) spin-up period
- Domain highly heterogeneous during summer period, and sampling data does not capture full lake state
    - Nutrient data not available in real-time

Data assimilation: modify forecast Day 0 conditions with available data

- Temperature and DO data from high-frequency monitoring
- Cyanobacteria concentrations from most recent satellite data
    - Data availability limited and only captures top of water column
- Nutrient data not available in real time



- Satellite cyanobacteria data
- Limited temperature profiles

Conclusions

- 3D hydrodynamic and water quality model of Inland Sea successfully calibrated for 6.5-year period

- Medium-term forecast framework implemented
  - Data assimilation efforts underway to generate startup conditions

- Work ongoing to enhance forecast evaluation and performance
  - Understanding of forecast sensitivity to input variables
  - Analysis of errors in satellite measurements

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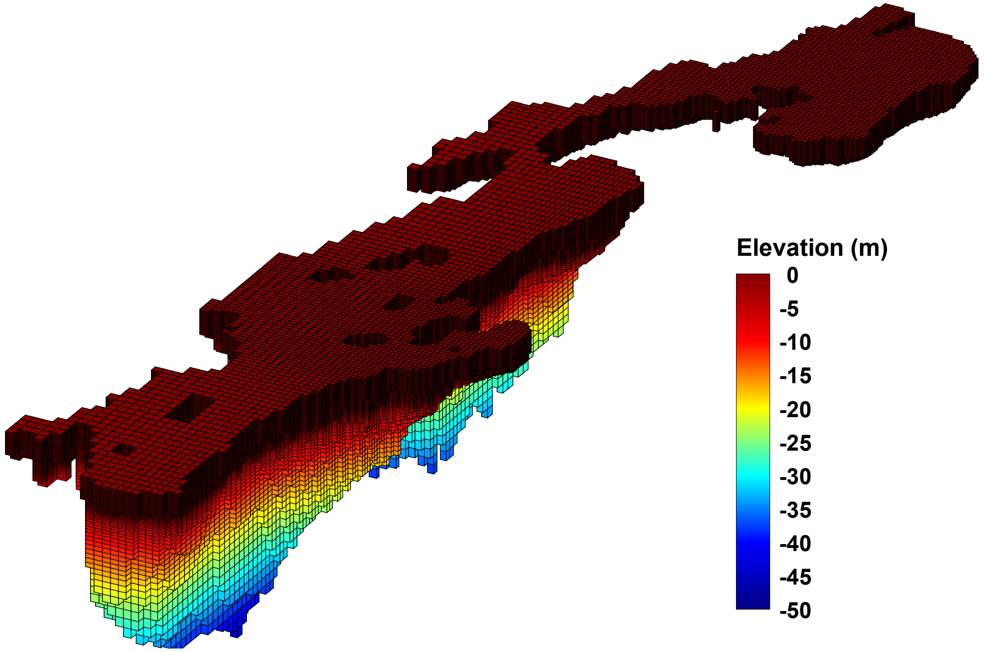
Future Opportunities

- Evaluate factors affecting forecasting results
- Incorporate enhancements to model inputs
  - Startup conditions
  - Consistency between historical and forecast weather data
  - Improvement to flow and nutrient loading forecasts
- Implement seasonal-scale forecasting framework



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Thank You

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Comparison between Satellite and Model Distribution