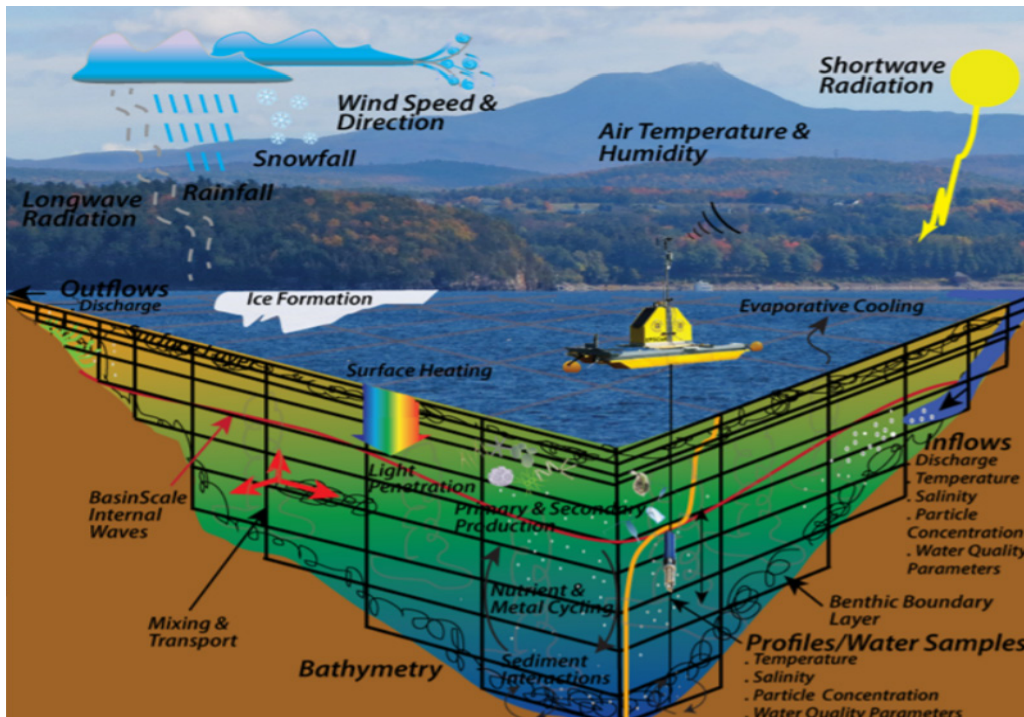# Hydrodynamic Modeling in Lake Champlain: Current Resources, Major Gaps

February 2021

Final Report

Prepared by:
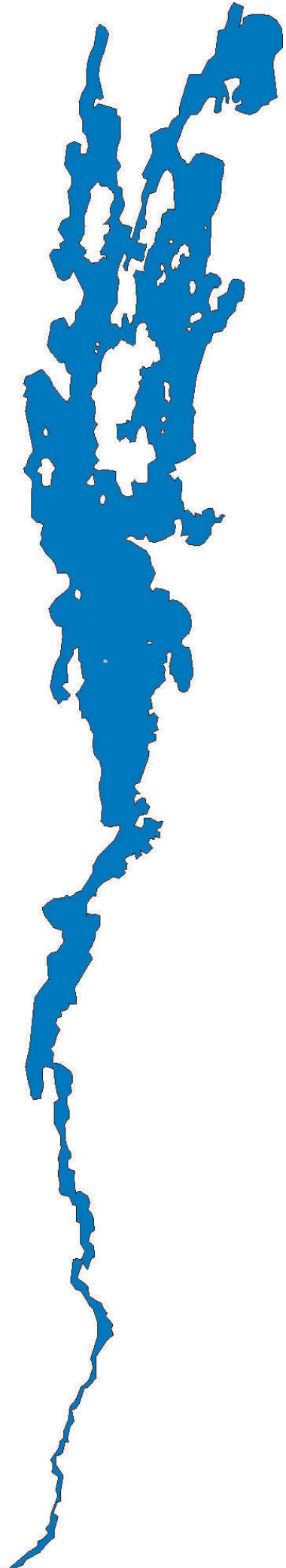Mae Kate Campbell, Lake Champlain Basin Program
Julianna M. White, Lake Champlain Sea Grant

For:
Federal Partners Working Group

Hydrodynamic Modeling in Lake Champlain:

Current Resources, Major Gaps

Compiled by Mae Kate Campbell
and Julianna M. White

Lake Champlain
Basin Program

Sea Grant
Lake Champlain

Overview and Recommendations

Hydrodynamic models are computer-based programs designed to simulate processes and movements in water bodies. Scientists and policymakers use the robust information produced by hydrodynamic models to improve our understanding and develop policies for the protection and future management of water bodies. Current environmental issues in Lake Champlain that are or could be informed by hydrodynamic models include excess nutrients, changing temperature dynamics, flooding, harmful algae blooms, pathogens, contaminants, and invasive species. Existing hydrodynamic models are currently used to forecast flood risk and to determine how seasonal water current and nutrient dynamics affect the occurrence of harmful algae blooms, among other applications.

In Lake Champlain, hydrodynamic models have been developed and utilized for a variety of purposes. This document summarizes early modeling efforts focused on Lake Champlain and describes five hydrodynamic models used to describe the hydrodynamics of the lake.

- Early Models
- 3-D Coupled Hydrodynamic-Biogeochemical Model of Lake Champlain
- Deltares DFLOW-Flexible Mesh Hydrodynamic Model
- Lake Champlain-Richelieu River 2D Hydrodynamic Model
- Lake Champlain Flood Forecasting System
- Lake Champlain Flood Forecasting System Wave Model
- MIKE 3 Flow Module

Hydrodynamic models have improved our understanding of lake dynamics; however, further research and modeling efforts are needed both to increase the accuracy of the models and to serve natural resource mangers' and policy-makers' science-based information needs.

Modelers indicate that the following critical gaps in knowledge and information in the Lake Champlain basin must be addressed:
- **Observations of incoming solar radiation**
- **Additional wind measurement sites over and within Lake Champlain**
- **Siting of meteorological stations**
- **Inclusion of river temperature measurements at all gauging stations**
- **Improved lake bottom bathymetry data, such as in-lake LiDAR**
- **Better characterization of the river and Champlain Canal discharge into the South Lake**

Early Models

While advances in computational power have allowed for the creation of more sophisticated and higher resolution models, early hydrodynamic modeling of Lake Champlain provided important information about lake dynamics and supported resource management. Initial models have been the building blocks for future models and pointed toward further research needs. Following are highlights of two early hydrodynamic models used to research and manage Lake Champlain.

Lake Champlain Hydrodynamic Model (1996)

The Lake Champlain Hydrodynamic Model was developed in the mid-1990s to study the circulation, mixing, and transport dynamics of water in Lake Champlain, with a focus on its response to wind and the formation of underwater waves along the boundaries between thermally-stratified layers. The Lake Champlain Phosphorus Model was developed in parallel to the Lake Champlain Hydrodynamic Model to study phosphorus dynamics with the goal that the two models may be applied either separately or as a system to inform management decisions. (Phosphorus is a leading cause of poor water quality in Lake Champlain.) Together, the two models allowed managers to monitor phosphorus and make management decisions to reduce phosphorus in Lake Champlain. Model simulations indicated that further studies were needed to better characterize lake circulation dynamics and document wind fields; related, more wind stations and current measurements in Mallets and Missisquoi Bays were particularly needed.
More information: Hydrodynamic and Water Quality Modeling of Lake Champlain (1996).

Missisquoi Bay Hydrodynamic Model (1997)

The Missisquoi Bay Hydrodynamic Model was developed to simulate currents and the transport, deposition, and flushing of sediment and phosphorus in Missisquoi Bay. The model was specifically crafted and applied to investigate the difference in hydrodynamic conditions in the bay with and without the existing Swanton-Alburg Route 78 bridge and causeway in response to concerns about deteriorating water quality. Model results indicated that the existing causeway did not hydraulically constrict the flow of water between the bay and the northeast arm of Lake Champlain; however, scenarios that modeled the removal of the causeway demonstrated a minor but consistent improvement in flushing and sedimentation rates. Model developers noted the need for field testing to verify these results and suggested that the model could be improved through the inclusion of wind speed data and river flow information accurate to Missisquoi Bay.
More information: Hydrodynamic Modeling of Missisquoi Bay in Lake Champlain (1997)

3-D Coupled Hydrodynamic–Biogeochemical Model of Lake Champlain

Applied the AEM3D computer-based model to Lake Champlain. It explores how underlying seasonal dynamics of water circulation influence nutrient cycling processes and occurrence of harmful algal blooms (HABs) and informs watershed and in-lake water quality management scenarios for lake restoration efforts.

Primary function: Simulates hydrodynamics, nutrients cycles, and food web dynamics across seasons in three dimensions.
Spatial coverage and resolution: All of Lake Champlain in three dimensions with a uniform horizontal grid size of 200 m by 200 m. Vertical resolution of 1 m in the first 20 m progressively increases to a maximum of 5 m at the lake bottom.
Output: Physical and biogeochemical features by time and space variables.
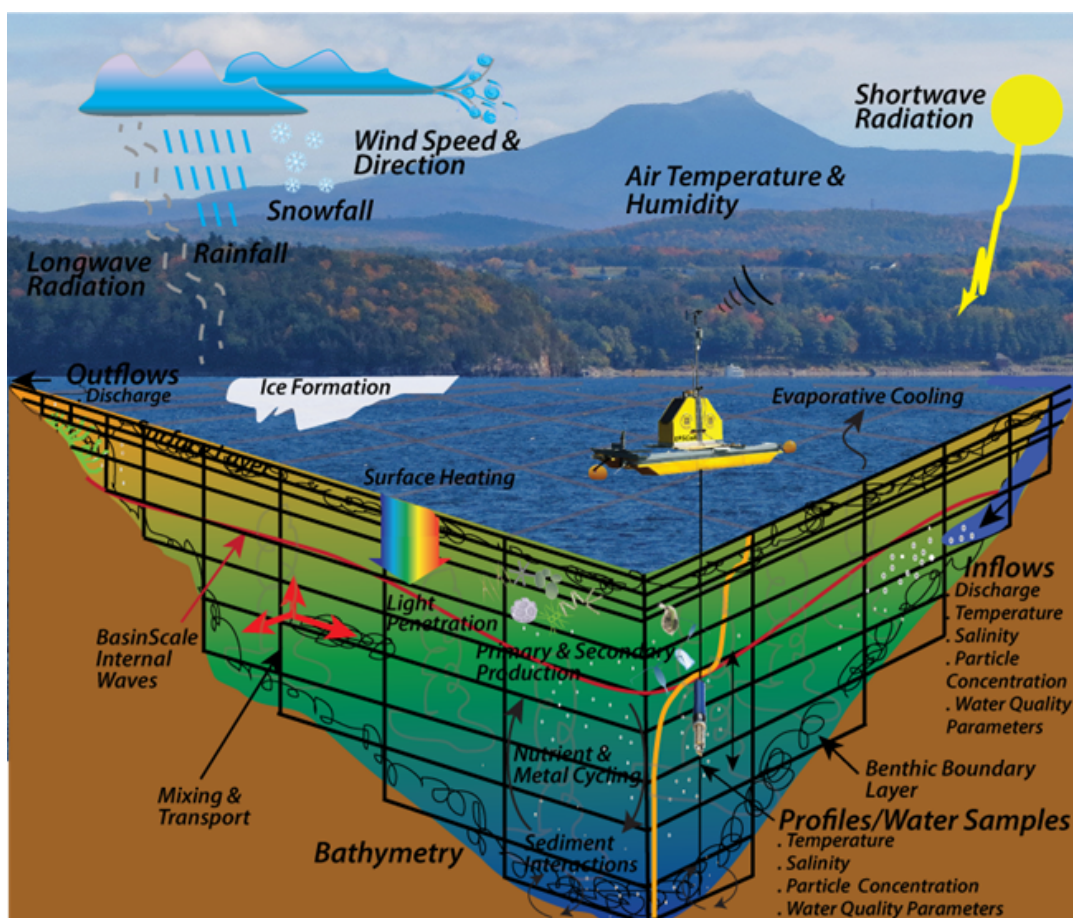**Access:** Via email at epscor@uvm.edu.

Image: Input data and key physical and biogeochemical processes simulated by the 3-D Coupled Hydrodynamic-Biogeochemical Model of Lake Champlain (Credit: Schematic developed by C. Marti)

3–D Coupled Hydrodynamic– Biogeochemical Model of Lake Champlain

Short history: The National Science Foundation (NSF) Vermont Established Program to Stimulate Competitive Research (EPSCoR) Basin Resilience to Extreme Events (BREE) project implemented the coupled three-dimensional (3D) hydrodynamic and biogeochemical model Aquatic Ecosystem Model 3D (AEM3D, formerly ELCOM-CAEDYM) in Lake Champlain with explicit focus on Missisquoi and Saint Albans Bays. The model uses existing spatial and temporal high-resolution field data, including meteorological, hydrological, physical and biogeochemical data, from a variety of sources for incoming tributaries, lake, and outflow. The data establish both initial conditions and boundary forcing, calibration and validation of the numerical model.

Applications/outcomes: The model will be embedded into an Integrated Assessment Model to assess annual to decadal scale impacts of climate change and extreme events on water quality in Missisquoi and Saint Albans Bays. The model is also used for scenario planning and long-range forecasting.

Sponsors/funders: National Science Foundation (NSF) OIA 1556770: Vermont Established Program to Stimulate Competitive Research (EPSCoR) Basin Resilience to Extreme Events (BREE) project

More information
- Modelling platform: Aquatic Ecosystem Model 3D (AEM3D), developed and distributed by HydroNumerics
- Marti CL, Schroth AW, and Zia A. 2019. Physical and biogeochemical processes across seasons in Missisquoi Bay, Lake Champlain: Insights from a three-dimensional model. AGU Fall Meeting, 9-13 December 2019, San Francisco, USA. Oral session. H34C-04.
- Clemins PJ, Turnbull S, Rodgers M, and Zia A. 2020. Implementing a loosely-coupled integrated assessment model in the Pegasus Workflow Management System. In Practice and Experience in Advanced Research Computing (PEARC '20), July 26–30, 2020, Portland, OR, USA. ACM, New York, NY, USA 5 Pages.
- Dr. Clelia Luisa Marti; Clelia.Marti-De-Ocampo@uvm.edu

Deltares DFLOW–Flexible Mesh Hydrodynamic Model

This 3-D, whole-lake model examines how circulation and temperature dynamics affect water intakes, likely surface movements of potential oil spills, residence times, and upwelling dynamics. Although not incorporated at this time, the model can also calculate wind-forced surface waves, sediment transport and water quality.

Primary function: Represents circulation and temperature dynamics in Lake Champlain from 2012 through 2019, incorporating actual atmospheric conditions and river discharges as measured during that time.

Spatial coverage and resolution: Whole lake, from south of Whitehall to Chambly in the north. It has 250 m horizontal resolution and 0.25 m resolution in the upper 6 m of the water column. Vertical dimension of the cells become larger with increasing depth.

Output: Velocity, temperature, water level and river water fate/age at specific locations at user-defined time intervals. Data is available at higher resolution at a select number of observation points. Data are output in ascii & netcdf formats.
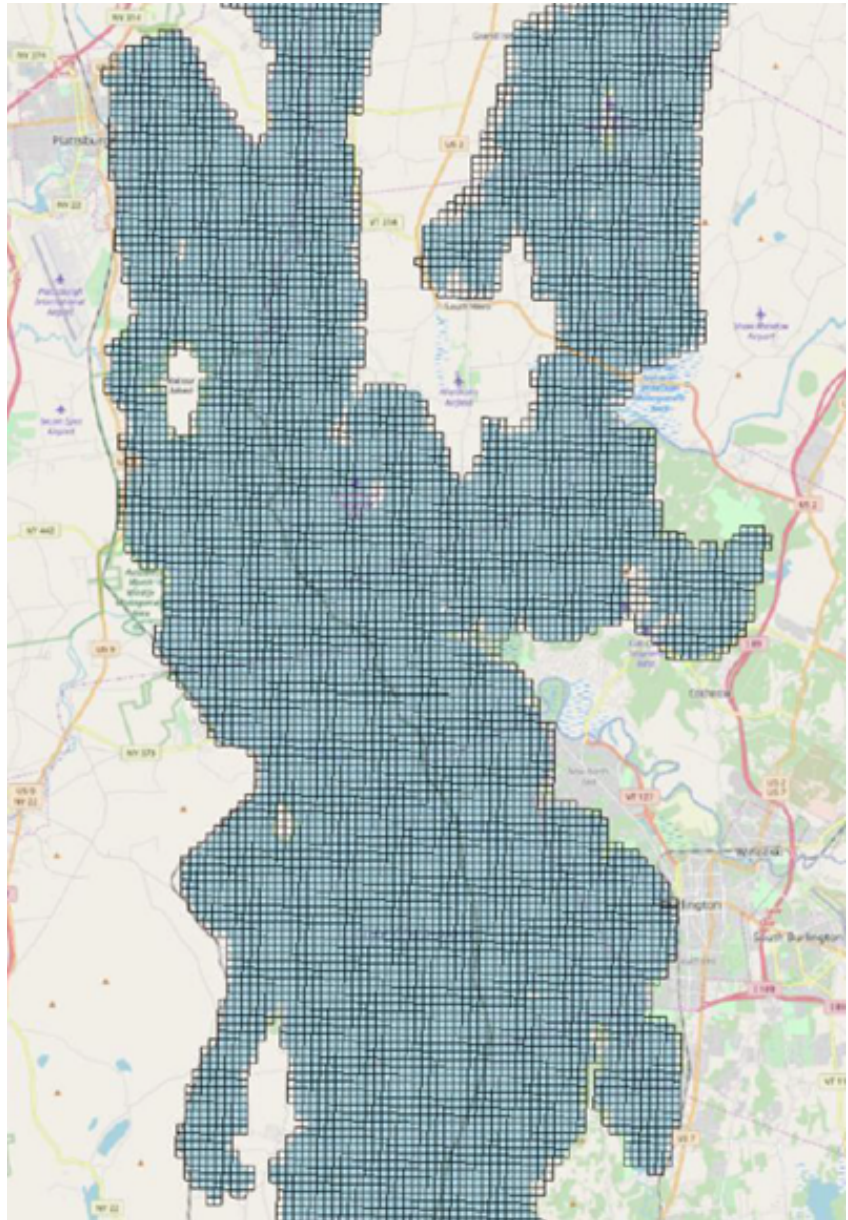

Image: Map view of Lake Champlain overlaid with the cells of the Deltares DFLOW-Flexible Mesh Hydrodynamic Model

Deltares DFLOW–Flexible Mesh Hydrodynamic Model

Access: Information available via email to Tom Manley (tmanley@middlebury.edu) or Liv Herdman (lherdman@usgs.gov).

Short history: This 3-D model was initially developed in 2012 to investigate the effects (presence or absence) of human built causeways on the circulation of Lake Champlain, with a focus on the effects of causeway removal within the Restricted Arm, which consists of Missisquoi Bay, the Inland Sea, Malletts Bay and the Alburg Channel. The model was developed by Liv Herdman and Tom Manley through work with Middlebury College students. The model has evolved into a whole-lake model with specific attention given to modifying observed river discharge measurements at various distances up river from lakeshore to that of a more realistic river discharge at the lakeshore, validation of observed water levels throughout the lake (achieved though significant contribution of the Canadian lake model group, Champoux), internal seiche dynamics, and typical causeway/passageway development and via flexible-mesh and cut-cell methodologies.

Applications/outcomes: Final models related to effects of causeways within the Restricted Arm of Lake Champlain are forthcoming. Preliminary results show that the removal of the Missisquoi Bay causeway would not, by itself, significantly change the outflow from Missisquoi Bay; however, the domino-effect from additional removals of causeways at Alburg Bridge and Carry Bay could alter that view. The presence/absence of other causeways within and bounding the Restricted Arm may significantly alter the flow patterns of the Inland Sea and Malletts Bay, with significant implications for water quality in the Restricted Arm. This model also showed the inadequacy of (typical) models with vertical cells of 1 m or larger in describing the complex vertical shear and 2-layer flow dynamics repeatedly observed within the very shallow (~3-4 m) Missisquoi Bay. Higher vertical-resolution models are required to adequately define this circulation and serve as a basis for management decisions.

Sponsors/funders: Middlebury College, National Science Foundation (NSF) OIA 1556770: Vermont Established Program to Stimulate Competitive Research (EPSCoR) Basin Resilience to Extreme Events (BREE) program, Lake Champlain Sea Grant

More information:
- Overview presentation (2018)
- *Causeways and Lake Circulation in Lake Champlain* presentation (2019)
- Dr. Liv Herdman's USGS staff profile
- Dr. Tom Manley's Middlebury College profile

Lake Champlain–Richelieu River 2D Hydrodynamic Model (H2D2)

The H2D2 hydrodynamic model covers the entire Lake Champlain and Richelieu River system from Whitehall, NY to Sorel, Québec, where the Lake reaches the Saint-Lawrence River. This high-resolution hydrodynamic model is able to precisely estimate water level and currents with an accuracy of around 5 cm. It was designed to describe flooded zones and to be used in a predictive mode by taking into account wind effects and plant growth. Results from this model are used by the IJC International Study on Lake Champlain – Richelieu River in a separate model that quantifies the social, economic, and environmental impacts of various flooding scenarios and proposed mitigation measures to address flooding.
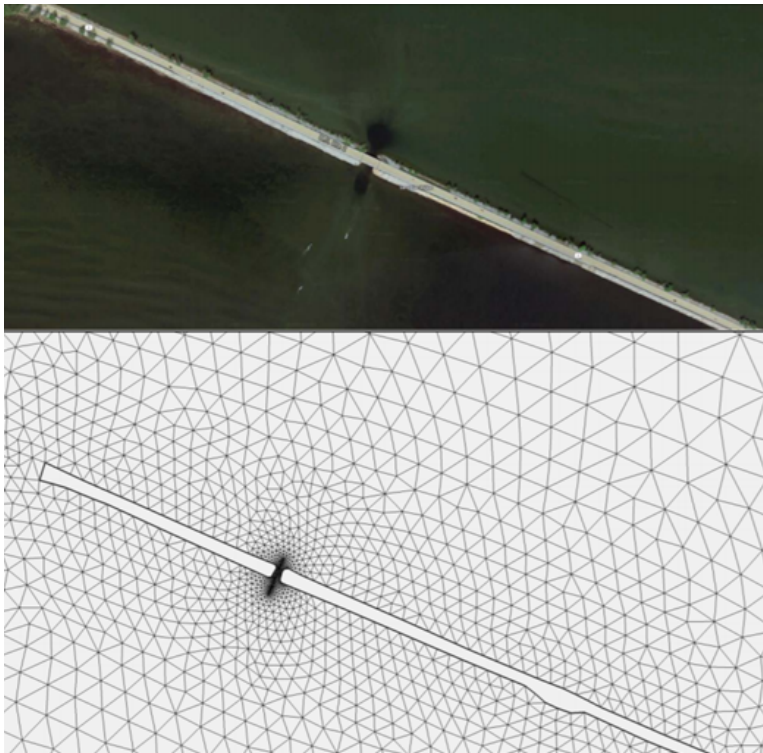

Primary Function: Simulates water flow across the Lake and through the Richelieu River to estimate water levels and local velocities. Inputs are the discharge values from Lake tributaries upstream and the Saint-Lawrence River water level in the lower part of the system.

Spatial coverage and resolution: Model simulates all of Lake Champlain and the Richelieu River using a finite-element two-dimensional hydraulic model. Resolution varies across the lake depending on local bathymetry variations. Element length averages 175m in the Lake and 25m in the River, with refinements down to a few meters where necessary.

Image: Aerial photo of US highway 2 between South Hero and Colchester, Vermont, and the corresponding mesh used in the Lake Champlain-Richelieu River 2D Hydrodynamic Model to simulate the hydraulic effects of this structure on water levels in Lake Champlain.

Output: Physical variables (water level, velocities, depth, etc.) at each point of the grid (water level, velocities). The model can be used either in a static mode (scenario) or in a transient-mode (time-based approach).

Lake Champlain–Richelieu River 2D
Hydrodynamic Model (H2D2)

Availability: This computer-based model is the property of the International Joint Commission. Inquiries can be sent directly to the IJC; model details will remain classified until the conclusion of the Lake Champlain - Richelieu River Study. Use requires programming knowledge and significant technical expertise.

Short history: The hydrodynamic model for the Lake and river was developed between 2017 and 2020 to provide local physical variables to the IJC Integrated Socio-Economic Environmental (ISEE) model, to estimate floodplain extension and to be used in a forecast mode. The 2D model covers the whole Lake and river up to the St. Lawrence River in Sorel, Québec, and has been calibrated using observation data from the past 40 years. The coupling of this hydrodynamic model to the ISEE system allows the comparison of various flood mitigation solutions and provides management tools to reduce the economic and ecological impact of these events.

Applications/outcomes: The primary use of the model is in its static form, using a range of lake discharge values (from 25 m3/s to 2500 m3/s), but the same model can be used in its transient form to simulate real-time & forecasted conditions. Wind and precipitation/evaporation from atmospheric models can be added easily as inputs to the model, although wind calibration brings its own sets of challenges due to the 2D equations. Workaround solutions exist and are being currently implemented.

Sponsors/funders: This model was developed by Environment Canada in coordination with the International Join Commission (IJC) Lake Champlain – Richelieu River Technical Working Group.

More information:
Boudreau P, Cantin JF, Bouhcard A, Champoux A, Fortin P, Fiset JM, Fortin N, Thérien J, Morin G. 2015. Development of an experimental 2D hydrodynamic model of Lake Champlain using existing bathymetric data. Technical report prepared by Environment Canada for the International Lake Champlain – Richelieu River Technical Working Group.

Lake Champlain Flood Forecasting System

National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL) and the Cooperative Institute for Great Lakes Research (CIGLR) aim to complete development and testing of a real-time hydrodynamic modeling system for the Lake Champlain-Richelieu River basin through the Lake Champlain Flood Forecasting System. This system will inform future operational flood forecasts for the Lake Champlain-Richelieu River system and support inundation mapping, recreational forecasts, and search-and-rescue efforts. As this model is under active development as of December 2020, all model results and associated data products are considered experimental.
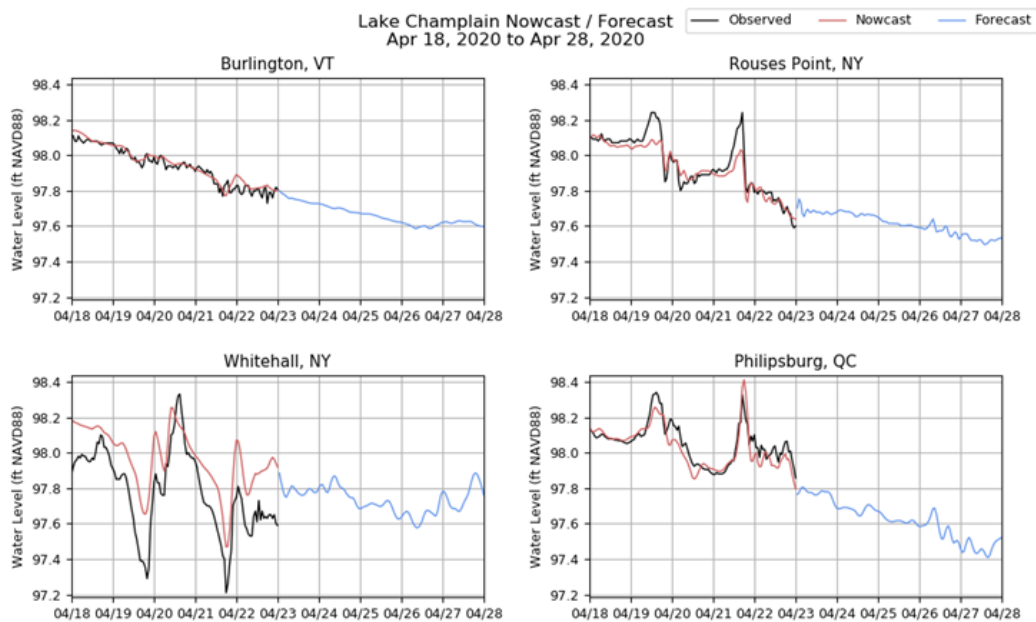

Image: Water level nowcast and forecast at select locations, April 18-28, 2020, produced by the Lake Champlain Flood Forecasting System

Primary function: The modeling system simulates the hydrodynamics of Lake Champlain, including water levels and water currents. It incorporates dynamic wetting and drying to simulate floodplain inundation. Inputs include river inflow data from the National Water Model and meteorological data from operational forecasting systems.

Spatial coverage and resolution: The domain covers all of Lake Champlain and the upper Richelieu River, as well as the surrounding floodplain. Resolution ranges from approximately 50 m in coastal areas up to approximately 350 m in deep offshore areas.

Output: The model outputs spatially-variable water levels, water currents, and the portions of the floodplain that are inundated. Five-day forecasts are produced daily, with hourly data generated for every model grid point over the forecast window.

Lake Champlain Flood Forecasting System

Access: Figures summarizing model output are updated in near real-time on a publicly accessible website (www.glerl.noaa.gov/res/champlain). Archived model data in netCDF format are available from November 2019 through present by emailing Jesse Feyen (jesse.feyen@noaa.gov) and Dmitry Beletsky (beletsky@umich.edu).

Short history: The Lake Champlain-Richelieu River forecasting system is being developed in response to recent floods caused by intense rain events and spring runoff. The Lake Champlain Flood Forecasting System builds upon an existing model, the Finite-Volume Coastal Ocean Model (FVCOM), which has been applied in other areas. This hydrodynamic model will address operational needs of the National Weather Service and the U.S. Coast Guard and provide input, particularly water levels, for Canadian flood models of the Richelieu River to enable improved flood forecasting. It improves upon existing, more simplistic hydrological models used for flood forecasting by simulating the localized effects of wind-driven storm surges.

Applications/outcomes: Model results will be used to support operational flood forecasts for the Lake Champlain basin. The five-day forecasts produced by the modeling system will allow forecasters to provide advanced warning of floods to residents and other stakeholders. Forecast results, such as water levels and water currents, will also be made available on a publicly-accessible website in a graphical format. This online tool is anticipated to benefit recreational activities on the lake (e.g. boating, fishing, beach-going), as well as search-and-rescue operations.

Sponsors/funders: This project is funded by the International Joint Commission (IJC) and is implemented by NOAA GLERL and the CIGLR.

More information:
- Website: www.glerl.noaa.gov/res/champlain
- Jesse Feyen (jesse.feyen@noaa.gov) and Dmitry Beletsky (beletsky@umich.edu)

Lake Champlain Flood Forecasting System Wave Model

The Lake Champlain Flood Forecasting System Wave Model works in conjunction with the Lake Champlain Flood Forecasting System. The Wave Model will contribute to the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL) and the Cooperative Institute for Great Lakes Research (CIGLR) completing development and testing of a real-time hydrodynamic modeling system for the Lake Champlain-Richelieu River basin. As with the Lake Champlain Flood Forecasting System, the Lake Champlain Flood Forecasting System Wave Model will inform future operational flood forecasts for the Lake Champlain-Richelieu River system and support inundation mapping, recreational forecasts, and search-and-rescue efforts. As this model is under active development as of December 2020, all model results and associated data products are considered experimental.
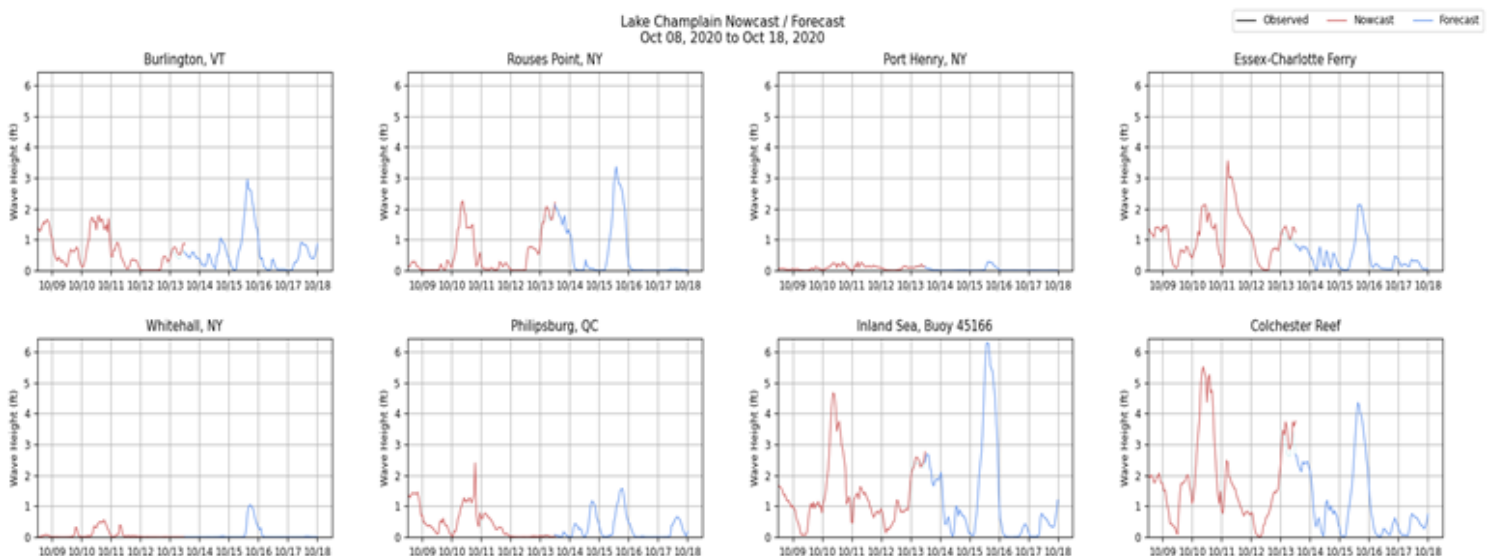

Image: Nowcast/forecast of wave heights at select locations in the Lake Champlain basin from October 8-18, 2020 produced by the Lake Champlain Flood Forecasting System Wave Model.

Primary function: The modeling system simulates the waves on the lake. It incorporates dynamic wetting and drying to simulate wave formation on inundated floodplain areas. Inputs include water level from the Lake Champlain Flood Forecasting system hydrodynamic model and meteorological data from operational forecasting systems.

Lake Champlain Flood Forecasting System
Wave Model

Spatial coverage and resolution: The domain covers all of Lake Champlain and the upper Richelieu River, as well as the surrounding floodplain. Resolution ranges from approximately 50 m in coastal areas up to approximately 350 m in deep offshore areas.

Output: The model outputs spatially-variable wave heights. Five-day forecasts are produced daily, with hourly data generated for every model grid point over the forecast window.

Access: Figures summarizing model output are updated in near real-time on a publicly accessible website (www.glerl.noaa.gov/res/champlain). Archived model data in netCDF format is available from August 2020 through present upon request by emailing Jesse Feyen (jesse.feyen@noaa.gov) and Dmitry Beletsky (beletsky@umich.edu).

Short history: The Lake Champlain-Richelieu River forecasting system is being developed in response to recent floods caused by intense rain events and spring runoff. This model adapts and existing NOAA hydrodynamic model template (WAVEWATCH III) for application in Lake Champlain. The wave model will address operational needs of the National Weather Service and the U.S. Coast Guard and will provide information about wave formation to enable improved flood forecasting and planning. The current models used for flood forecasting on Lake Champlain do not incorporate wave height predictions, making this model an important advancement.

Applications/outcomes: Model results will be used to support operational flood forecasts for the Lake Champlain basin. The five-day forecasts produced by the modeling system will allow forecasters to provide advanced warning of flood impacts to residents and other stakeholders. Forecast wave heights will also be made available on a publicly-accessible website in a graphical format. This online tool is anticipated to benefit recreational activities on the lake (e.g. boating, fishing, beach-going), as well as search-and-rescue operations.

Sponsors/funders: This project is funded by the International Joint Commission (IJC) and is implemented by NOAA GLERL and the CIGLR.

More information:
Website: www.glerl.noaa.gov/res/champlain
Jesse Feyen (jesse.feyen@noaa.gov) and Dmitry Beletsky (beletsky@umich.edu)

MIKE 3 Flow Model

The MIKE 3 Flow Module model of Lake Champlain was developed in 2014 to estimate the potential water quality impact of installing the New England Clean Power Link (NECPL), a proposed 98-mile high voltage direct current electric transmission cable running north-south in the bed of Lake Champlain.

Primary function: MIKE 3 provides 3D simulation tools to model free water surface flows and associated sediment or water quality processes. Used to assess hydrographic conditions for design, construction, operation, or environmental impact of structures in stratified waters; optimization of disposal outlets; optimization of aquaculture systems, lake hydrodynamics and ecology, etc.

Spatial coverage and resolution: Varies according to input. The Lake Champlain model was completed with 15-meter (50 foot) square element resolution in five locations, and coarser resolution at other locations.

Output: 3D models, tables, charts, maps, and videos.

Access: Lake Champlain Water Quality Modeling Report.
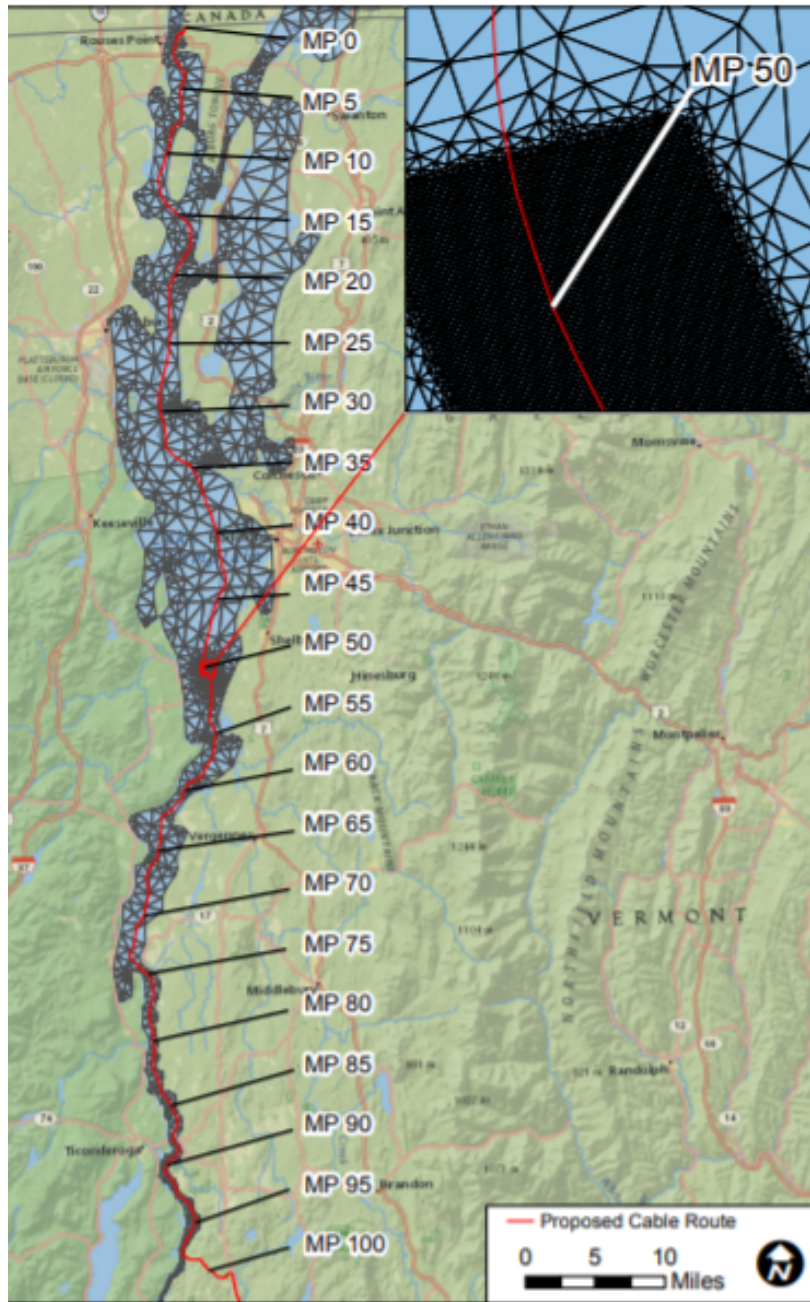

Image: Map shown in the Lake Champlain Water Quality monitoring report. Black lines over the lake demonstrate the model grid. The "MP" annotations refer to the mile point of the proposed cable length.

MIKE 3 Flow Model

Short history: MIKE Powered by DHI models and software products are well-known. MIKE 3 provides 3D modelling of water environments, and incorporates the 2D modelling framework from its predecessor, MIKE 21. MIKE 3 was employed for Lake Champlain in 2014 to assess the potential impact of installation of the NECPL on resuspension of sediments, and thus water quality. Five representative locations were used to model maximum concentrations over time to present the relative time duration of water quality concentration increases associated with the cable installation.

Applications/outcomes. MIKE 3 showed that the expected impact of cable installation on concentrations of total suspended solids (TSS), particulate phosphorus (PP), dissolved phosphorus (DP), and eight metals (arsenic, cadmium, copper, lead, nickel, zinc, silver and mercury) would be "minimal." TSS and DP would increase over a period of less than one hour and return to close to the normal level within one to four hours. All metal concentration changes would comply with applicable Vermont Water Quality Standards. NECPL is currently on hold.

Sponsors/funders. The Danish Hydraulic Institute (DHI), a private company that provides research, consultancy, technology, and training to solve a variety of water challenges, conducted the study with funding from Champlain VT, LLC, d/b/a TDI-New England (TDI-NE), the company that was proposing the NECPL.

More information:
- MIKE 3 website
- DHI website

The Federal Partners Working Group of the Lake Champlain Basin
identified a need to better understand the state of hydrodynamic modeling in the Lake Champlain Basin, given the importance of hydrodynamic models to improving our understanding of lake dynamics. This white paper summarizes current models and identifies unmet information needs.

Member organizations of the Federal Partners Working Group of the Lake Champlain Basin are:
- Lake Champlain Sea Grant – University of Vermont, Plattsburgh SUNY, NOAA
- National Oceanic and Atmospheric Administration
- National Park Service
- Natural Resources Conservation Service – USDA
- US Army Corps of Engineers – New York District
- US Coast Guard
- US Department of Agriculture (USDA)
- US Environmental Protection Agency, Region 1 (New England)
- US Environmental Protection Agency, Region 2 (New York)
- US Fish and Wildlife Service – Lake Champlain Fish and Wildlife Resources Office
- US Forest Service – Green Mountain National Forest
- US Geological Survey

This white paper was compiled and edited by Mae Kate Campbell, Lake Champlain Basin Program, and Julianna White, Lake Champlain Sea Grant, with the help of scientists involved in the development and implementation of each model. They are:
- Clelia Marti, 3-D Coupled Hydrodynamic-Biogeochemical Model of Lake Champlain
- Liv Herdman and Tom Manley, Deltares DFLOW-Flexible Mesh Hydrodynamic Model
- Rémi Gosselin, Lake Champlain-Richelieu River 2D Hydrodynamic Model
- Dmitry Beletsky and Daniel Titze, Lake Champlain Flood Forecasting System and Lake Champlain Flood Forecasting System Wave Model