Development of a Binational Flood Forecasting and Real-time Flood Plain Mapping System for Operational Implementation

International Lake Champlain - Richelieu River Study

A REPORT TO THE INTERNATIONAL JOINT COMMISSION

Submitted by

Jesse Feyen, Ph.D.
Dominic Roussel, P.Eng., M.Sc.
William Saunders
Vincent Fortin, Ph. D.

Hydrology, Hydraulics and Mapping (HHM)
Technical Work Group

June 2022

ACKNOWLEDGMENTS

The authors would like to thank the Flood Management and Mitigation Measures (FMMM) Technical Work Group for their valuable assistance in the development of this report. The contributions of Syed Moin, Bill Werick and Ted Yuzik are gratefully acknowledged.

This report received valuable review and comments from the Study Board members and study managers

INTERNATIONAL LAKE CHAMPLAIN-RICHELIEU RIVER STUDY BOARD

Co-chair, Canada

Jean-François Cantin

Co-chair, United States

Deborah H. Lee

Members, Canada

Michel Jean

Daniel Leblanc

Madeleine Papineau

Richard Turcotte

Members, United States

Eric Day

Ann Ruzow Holland

Pete LaFlamme

Kristine Stepenuck

Study co-manager, Canada

Serge Villeneuve

Study co-manager, United States

Mae Kate Campbell

This report was produced by the Hydraulics and Mapping (HHM) Technical Working Group (TWG) of the International Lake Champlain-Richelieu River Study Board.

TECHNICAL WORKING GROUP

HMM, Canada

Jean Morin

Milena Dimitrijevic

Olivier Champoux

Dominic Roussel

Simon Lachance-Cloutier

HHM, United States

Jesse Feyen

Bill Saunders

Chris Gazoorian

Tim Calappi

Blaine Hastings

EXECUTIVE SUMMARY

This report describes the recommended flood forecasting system (FFS) for the Lake Champlain and Richelieu River (LCRR) basin based on currently existing forecasting services, user needs, products, warning systems, and new tools and models provided by the International Lake Champlain and Richelieu River Study. This report addresses Objective 5.6 of the Study Plan.

STUDY FOCUS

There is no single binational official flood forecast for the entire LCRR watershed. Instead, agencies in each country, namely the National Oceanic and Atmospheric Administration (NOAA) in the United States and the Ministère de l'Environnement et de la Lutte contre les Changements climatiques[1] (MELCC) in Canada, are responsible for issuing official flood forecasts for their respective territories and producing a coherent binational forecast for the LCRR system at the international boundary. This will continue to be the case with the recommended flood forecasting system. However, the various components (i.e. models) are and will be deployed within Environment and Climate Change Canada (ECCC), NOAA and MELCC, with the latter two being responsible for official flood forecasting and ECCC, a partner of MELCC for hydrological modelling. The Study assessed the status of existing flood forecast models and determined that numerous gaps existed in the capacity of existing modelling systems on both sides of the border that limit the accuracy of forecast guidance available to official government forecasters.

APPROACH

With regard to new forecasting products, an assessment of users' needs highlighted that the desired products include not only currently produced graphs and data, but also near-term inundation maps with associated probabilities of occurrence or exceedance, and long-term probabilistic water level and flow graphs assessing the flood risk. The recommended FFS would use existing forecast systems, as well as models developed or improved during the LCRR study that are able to capture the processes relevant to forecasting on the LCRR, such as snow accumulation and snowmelt, inflows to Lake Champlain, discharge through the Richelieu River, wind and wave effects. These models and the use of ensemble forecasting will also enable uncertainty assessment, as well as mapping of the flood forecast. If the Study's recommended forecast system developments are adopted for use by official government forecast agencies, these improved models and systems will need to be transitioned and accepted for operations by those agencies.

[1] Ministry of the Environment and the Fight against Climate Change

Gap analysis between the current situation and the recommended system highlighted the fact that the required modelling improvements are ready, but still require some work to connect to each other, provide output data in useful ways, and be deployed in operational systems. The various actions needed are on the right track and no major technical barriers exist. Some research is still required to find a proper integration methodology for multiple forecast integration, but a hands-on approach by the forecasters can be leveraged in the meantime.

While no major technical barriers exist, it is important to point out that the various agencies (NOAA, ECCC and MELCC) have different institutional settings and will not be able to move at the same pace towards the fulfilment of all recommendations. Since coordinated forecasting services are already provided today, no specific shared completion deadline for modelling and forecasting upgrades needs to be recommended at this point. However, the respective forecasting agencies should transition the recommended modelling upgrades to operations as soon as possible.

The current governance model consists of matching forecast conditions in the Richelieu River at the international border, and will also be suited for the recommended system. There is no technical incentive justifying a change to more formal structures as no limitations were identified with the current one.

The various agencies (ECCC, MELCC and NOAA) need only to maintain their current collaboration and readily provide the necessary data to each other in other to maintain the forecasting chain as water flows from Lake Champlain across the border into the Richelieu River. If a structural mitigation measure is deployed (such as selective excavation of the shoal with a submerged weir and a modest Chambly Canal diversion), the FFS will need to provide input to any necessary management rules, and account for a mitigation measure's effect on water levels. Forecasts will also be readily provided to the manager of the diversion.

OUTCOME

The IJC LCRR Study enabled the development of improved tools which are now available to complete the deployment of the recommended flood forecasting system. Some work is still required to transition these improved forecasting tools to operations, but this can be undertaken by the various agencies without any major development work. Figure 1 presents a simplified illustration of the recommended FFS.

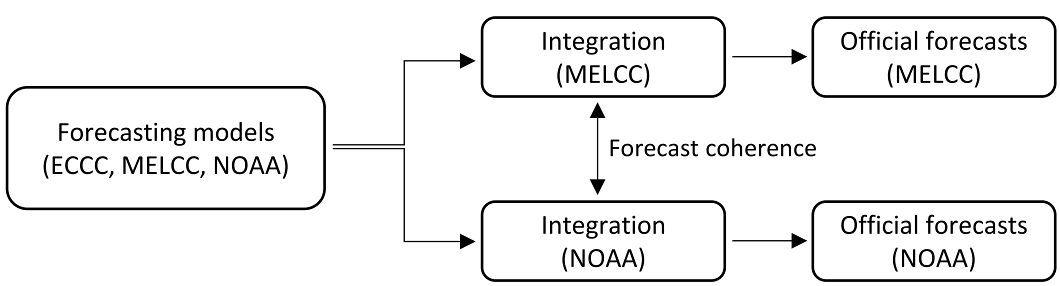


Figure 1. Simplified view of the recommended FFS.

THE INTERNATIONAL JOINT COMMISSION

Under the Boundary Waters Treaty of 1909 (the Treaty), the governments of the United States and Canada established the basic principles for managing many water-related issues along their shared international boundary. The Treaty established the IJC as a permanent international organization to advise and assist the governments on a range of water management issues. The IJC has two main responsibilities: regulating shared water uses; and investigating transboundary issues and recommending solutions.

STAY CONNECTED, BE ENGAGED

Want more information on the Lake Champlain-Richelieu River Study? Have a question for the Study Board?

Email the Study at lcrr@ijc.org

Sign up to receive Study news, such as notices of public meetings, consultations, reports, fact sheets, and other publications.

Follow the Study on social media

@IJCsharedwaters

www.facebook.com/internationaljointcommission/

www.linkedin.com/company/international-joint-commission/

TABLE OF CONTENTS

List of Figures

Appendix D

Appendix F

Appendix G

List of Tables

List of Acronyms

AHPS	Advanced Hydrologic Prediction System
COG	Centre des opérations gouvernementales (within MSP)
ECCC	Environment and Climate Change Canada
LCRR	Lake Champlain and Richelieu River
FFS	Flood Forecasting System
FMMM	Flood Management and Mitigation Measures Technical Working Group
HHM-T	Hydrology, Hydraulics and Mapping Technical Working Group
IJC	International Joint Commission
INRS-ET	Institut Nationale de la Recherche Scientifique – Centre Eau, Terre et Environnement
MELCC	Ministère de l'Environnement et de la Lutte contre les Changements climatiques
MSP	Ministère de la Sécurité Publique
MSP-D	MSPs Directions régionales
NERFC	Northeast River Forecast Center (RFC within NOAA)
NOAA	National Oceanic and Atmospheric Administration
NSRPS	ECCC's National Surface and River Prediction System
NWS	National Weather Service (within NOAA)
OAR	Office of Oceanic and Atmospheric Research (within NOAA)
ORSC	Organisation régionale de la sécurité civile
OSCQ	Organisation de la Sécurité Civile du Québec
OWP	Office of Water Prediction (within NOAA)
RFC	River Forecast Centers (within NOAA)
SWE	Snow water equivalent
WFO	Advanced Hydrologic Prediction System

1 INTRODUCTION TO THE REPORT

The purpose of this report is to make recommendations to support binational flood forecasting for the Lake Champlain and Richelieu River (LCRR) watershed based upon forecasting needs and operational requirements.

Operational flood forecasting is conducted by officially designated agencies in both the United States and Canada using a variety of data sources as input, including observations and a wide range of specialized environmental forecast models (e.g., weather, hydrologic, hydraulic and similar models). These daily forecasts are human-generated, constructed by highly trained expert forecasters within hardened, robust Information Technology systems that disseminate products and services and support user needs on a daily basis and in emergency situations. Forecasts are provided by official government agencies that have been authorized and mandated to deliver these public services to the taxpayers that have funded them. Therefore, US forecasts are provided on the US side of the border, while Canadian forecasts cover Canada.

The term Flood Forecasting System (FFS) is quite general, covering a range of technologies and activities used in forecasting. To simplify, a FFS is a system that provides, on a regular basis, forecasting products describing flood conditions (particularly water level and the resulting flood depth and extent). These products can range from simple short-term forecast water levels at specific locations to more complex products such as a map of water depth with a probability of occurrence (for example, 75% chance of non-exceedance). These forecasts can then be correlated to flood impacts such as number of buildings flooded, critical facilities affected, projected losses, and similar issues. However, these impacts are typically beyond the scope of the forecast itself and so are excluded from the analysis presented here. To provide these products, a FFS needs to continually run simulations of various models (mainly hydrological and hydrodynamic) to convert weather predictions and conditions on the watershed to guidance for flood forecasts. Hydrological forecasters assess the results and interact with the FFS to produce an official forecast that can then be disseminated to the users.

There are typically multiple sources of guidance[2] available to forecasters to use to create their forecasts. Forecast guidance typically refers to the computer-generated materials used to assist the preparation of a forecast, such as numerical forecast models. Often, multiple models are available to forecasters because they may be designed for different operational needs or may be in development for future operations. For a binational system like this one, it is often that the modelling systems from forecasting agencies on both sides of the border overlap in order to represent the entire system (i.e., the Lake Champlain-Richelieu River basin, in this case). Generally, nothing forbids these various model simulations from being produced by different agencies for the same watershed. For instance, the weather forecast can be produced in one agency, then passed to another that uses it as an input in a hydrological model of streamflow and routing. Multiple agencies can even predict the same variable such as water level/stage or flow. In fact, recent scientific research points toward the use of multiple sources of guidance to create forecasts to produce better results than those obtained with a single

[2] The term “guidance” or “guidance forecast” throughout this report refers to a model output that is available. A forecaster can then manually or automatically select a guidance or combine multiple guidances (for example, averaging them) to produce an official forecast.

source. Operational forecasters are trained and experienced in utilizing multiple models and data to generate a forecast, and use forecasting systems and their experience to synthesize the inputs into a forecast.

If nothing prohibits multiple agencies from producing multiple sources of guidance for forecasts, it is important that the official forecast be produced by highly trained experts from the official forecast agency, to avoid confusion for the users, general public and emergency responders alike. By producing the official forecast, this agency has the responsibility to provide products including official warnings, and to explain the details (and their limits) to the users who do not have the scientific expertise to do so themselves. This avoids the situation where a contradictory message arises from multiple forecasts.

The LCRR watershed's transboundary nature adds another important aspect to consider. In this case, there is no single binational official forecast for the entire watershed. Instead, agencies in both countries, namely the National Oceanic and Atmospheric Administration (NOAA) in the United States and the Ministère de l'Environnement et de la Lutte contre les Changements climatiques (MELCC) in Canada are responsible for issuing official flood forecasts for their respective territories.

Since water does not conform to administrative boundaries, users could still be exposed to contradictory messages if, for instance, the NOAA official forecast (upstream) predicts flooding conditions near the border when the MELCC official forecast (downstream) does not. It is thus important that the two official forecasts be coherent. Fortunately, this situation has never occurred because of the operational procedures in place and followed by the forecasters from MELCC and NOAA.

Additionally, even if the official forecasts are coherent, flood forecasting products still need to be easily understandable and useful to the users, whether they may be emergency managers, first responders, the media or the general public. Thus, it is important that user needs for forecasting products be considered and compared against what is technically feasible in operations. This will ensure the relevance of the FFS itself.

This report addresses Objective 5.6 of the International Joint Commission (IJC) LCRR Study. This objective requires the recommendation of a state-of-the-art binational flood forecasting system and an explanation of the various steps needed to implement it with regards to the currently existing FFSs. To address this objective, the report starts by listing the requirements of such a system. Then, with respect to the institutional setting of flood forecasting in Canada and the US, it identifies the technical gaps and the steps needed to fill them. Governance of the system is also discussed, and a general picture is provided on how new forecasting products could be used to improve flood response.

2 INSTITUTIONAL SETTING AND REQUIREMENTS

To understand the process for generating and disseminating official flood forecasts, and the recommended improvements in both nations' FFS in the following sections, the different institutional settings and requirements in both Canada and the United States must be described. Working within this context is critical to the success of any improvements to operational flood forecasting, as these are large, complex national and provincial systems with operational constraints and requirements. Despite differences in FFS that exist between the two countries, each approach has proved to be effective and provides critical components of the forecasting enterprise, and meaningful collaborations exist between the different agencies. Further details are described below.

2.1 FLOOD FORECASTING IN THE UNITED STATES

Flood forecasting is a federal mandate in the United States, which employs a structured and formal national review and approval process. NOAA has the authority to develop and disseminate weather and water forecasts, including for floods. NOAA carries out this mandate via collaboration between its research and development (R&D) laboratories, national centers, regional and localized offices. Weather forecast services, including product dissemination and communication with media and emergency managers, are conducted by NOAA's National Weather Service (NWS). NWS often works with partners such as NOAA's Office of Oceanic and Atmospheric Research (OAR), other federal agencies and academia to develop and test improved sources of guidance for weather, water and flood forecasts, as well as to advance products, messaging and outreach. Local emergency managers at the county or city level are responsible for conducting emergency response activities based upon these forecasts and for protecting local populations.

Figure 2 outlines the flood forecasting process in the United States. The NWS produces river forecasts (time series of flow and/or stage) through their regional River Forecast Centers (RFCs). There are 12 RFCs in the conterminous United States and a 13th RFC in Alaska. The Northeast River Forecast Center (NERFC) produces forecasts for over 200 discrete river locations across New England and eastern New York. Forecasts from the NERFC are passed to the eight Weather Forecast Offices (WFOs) in the region. The WFOs have the responsibility of publishing the forecasts and providing decision support services immediately prior to and during flooding by providing watches, warnings and situational awareness briefs to decision makers, via email or other correspondence mechanisms.

2.2 FLOOD FORECASTING IN QUÉBEC (CANADA)

In Canada, weather forecasting is a federal mandate, whereas flood forecasting is a provincial responsibility. Figure 3 outlines the flood forecasting process in Canada. At the federal level, ECCC produces weather forecasting for the entire country. Within the Government of Québec, MELCC is responsible for producing the forecast and the Ministère de la Sécurité Publique (MSP) is responsible for supporting emergency responders within cities and municipalities. Dissemination is done via both the MELCC and MSP websites. MELCC's forecasting team is completely autonomous with its forecasting processes. ECCC produces operational hydrological forecasts to support federal mandates other than flood forecasting.

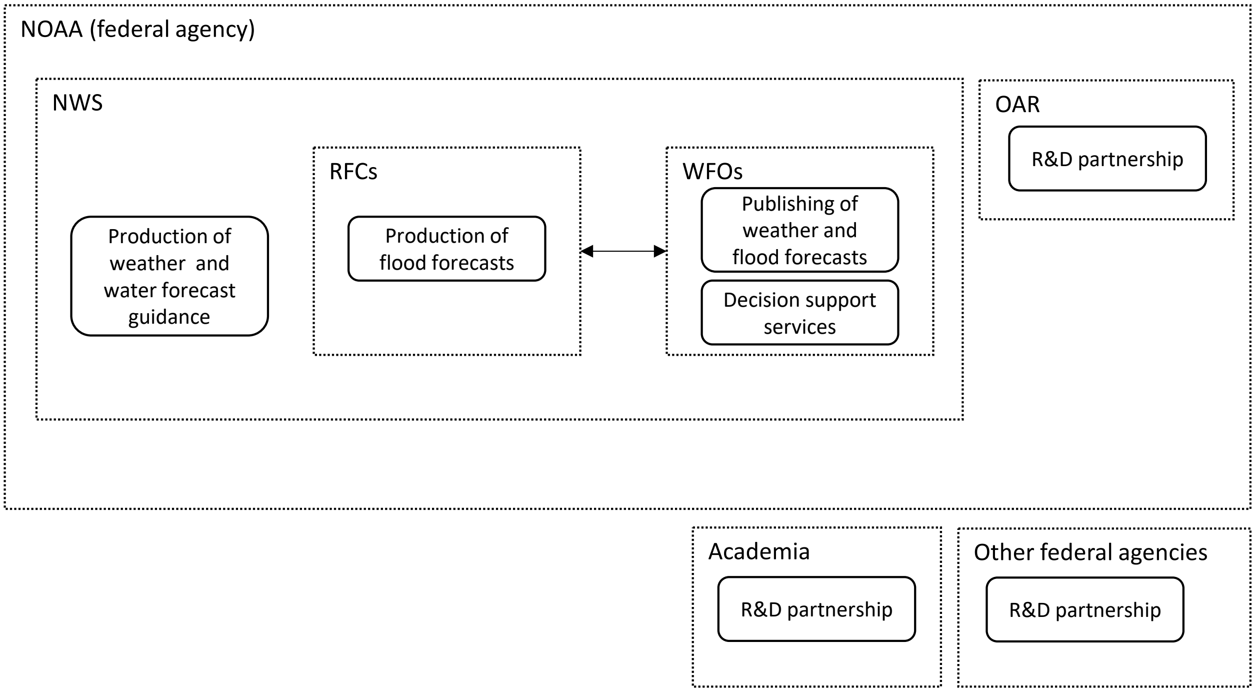


Figure 2. United States institutional setting.

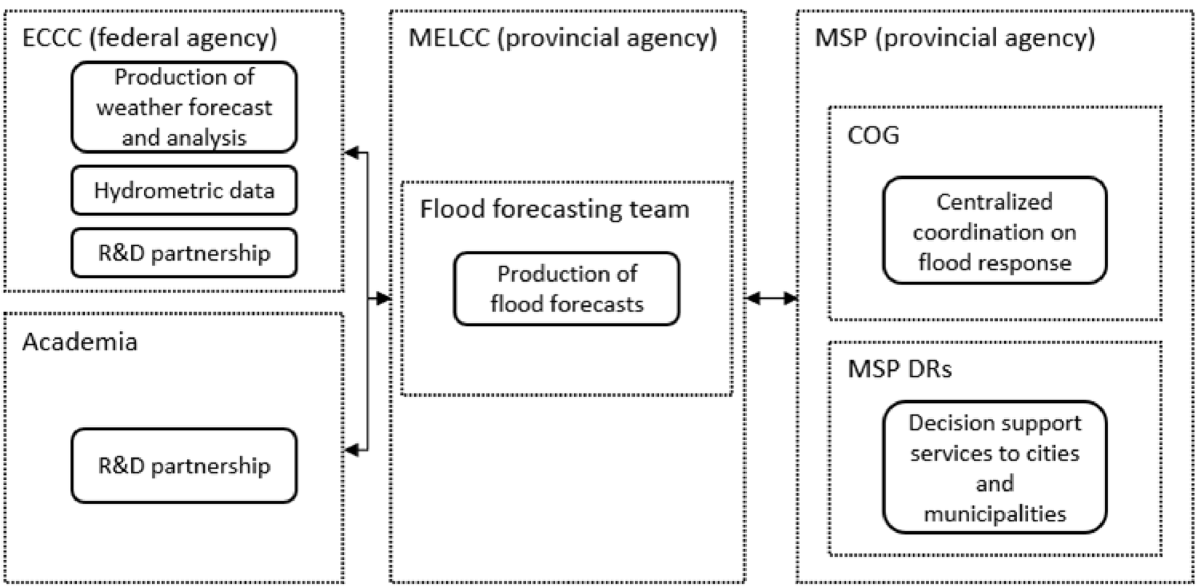


Figure 3. Canada institutional setting.

It is worth mentioning that MELCC has a centralized team responsible for all aspects of the flood forecast production for the whole territory. This team of forecasters produces the forecasts and develops, maintains and implements the various modelling components that form the FFS. It also maintains collaboration with ECCC and academia for R&D projects specifically on forecasting. Other academia projects can be coordinated by MSP as well on the broader subject of flooding. Before, during and after flood events, MELCC provides ongoing expertise and decision support to the MSP.

MSP has a centralized operation office, the Centre des opérations gouvernementales (COG), which is responsible for emergency response coordination for flooding, among other hazards. The MSP then breaks down its support activities to the cities and municipalities via various regional offices called directions regionals (MSP-DR).

At first glance, this system can seem puzzling, but it has, in fact, been operating successfully for more than 10 years. It is important to keep in mind that all during operations, R&D partnership is not present and all data and information is automated or strictly procedured.

2.3 BINATIONAL COLLABORATION FOR LCRR FLOOD FORECASTS

MELCC started producing forecasts for the Richelieu River in 2012, following the 2011 major flooding event. To do so, MELCC has been using NERFC forecasts of water levels at Rouses Point as a boundary condition for their own forecasts, meaning US and Canadian forecasts are directly linked. Since then, MELCC and NERFC forecasters have been collaborating during flood events to ensure coherence between flood forecasts on both sides of the border. Current flood forecasts available for the LCRR system are being produced by this binational collaboration. Currently, non-coherent forecasts cannot really occur, since MELCC is starting their forecast using NERFC forecasts that have been coordinated at Rouses Point. Even though it has not happened in more than 10 years, if MELCC forecasters would find any issues with the NERFC forecast, they would directly communicate with the NERFC forecaster responsible for the forecast to discuss any concerns and they would jointly resolve the issue. More details can be found in APPENDIX F – Forecasting services and skill metrics for Canada.

3 FLOOD FORECASTING AND MAPPING SYSTEM REQUIREMENTS FOR THE LAKE CHAMPLAIN AND RICHELIEU RIVER SYSTEM

After the 2011 historical flood, there was wide-spread support for a better flood forecasting system in the LCRR basin. In 2011, the NERFC provided accurate forecasts, but lacked specific model guidance for some important phenomena. The simple, one-dimensional hydraulic model used to predict Lake Champlain lake levels is based upon observed and projected hydrologic inflows. However, it lacks the capacity to account for wind-driven effects, including coastal flooding driven by storm surges and seiches. There also wasn't a wind wave model to predict wave heights and the corresponding wave impacts along shorelines. The IJC spear-headed this effort and produced a report entitled, "Progress towards an operational real-time flood forecasting and flood inundation mapping system for the Lake Champlain and Richelieu River" (IJC 2015). The report clearly lays out the functionality and specific requirements for the proposed system.

In 2016, the IJC received a reference from the governments to examine ways to better mitigate flooding in the LCRR basin and established the International Lake Champlain-Richelieu River Study (ILCRRS). The Study was directed to address seven key objectives. The fourth objective was:

Developing and making recommendations for implementing, as appropriate, an operational, real-time flood forecasting and flood inundation mapping system for the Lake Champlain-Richelieu River watershed.

This report addresses this objective and builds upon the requirements identified in the 2015 IJC report.

3.1 FLOOD EMERGENCY RESPONDERS' NEEDS

Emergency responders were solicited on both sides of the border as to their needs for products and services required from the flood forecasting and inundation mapping system. Engaging emergency responders during the Covid-19 pandemic presented challenges, but provided useful feedback. As can be expected, the needs that were expressed are different on the US side than on the Canadian side. The US side of the LCRR system is comprised of Lake Champlain, a lacustrine environment, whereas a riverine environment, the Richelieu River, comprises most of the Canadian portion of the system (except for Missisquoi Bay). The hydraulic conditions make the system response time for rising water levels slower in the United States (i.e., lake) than in Canada (i.e., river). Activities such as flood retention and floodplain management have been undertaken on both sides of the border, with flooding along the lake shore becoming less of an issue with time. All these factors impacted the level of interest and feedback received regarding emergency responders' needs. Details of the needs assessment process can be found in APPENDIX A – Flood emergency responders' needs assessment.

3.2 RECOMMENDED FFS OVERVIEW

Based on the information gleaned from the emergency responders' needs assessment, a recommended FFS framework was developed. Figure 4 presents an overview of the recommended binational flood forecasting system; the various components are described in the following sections.

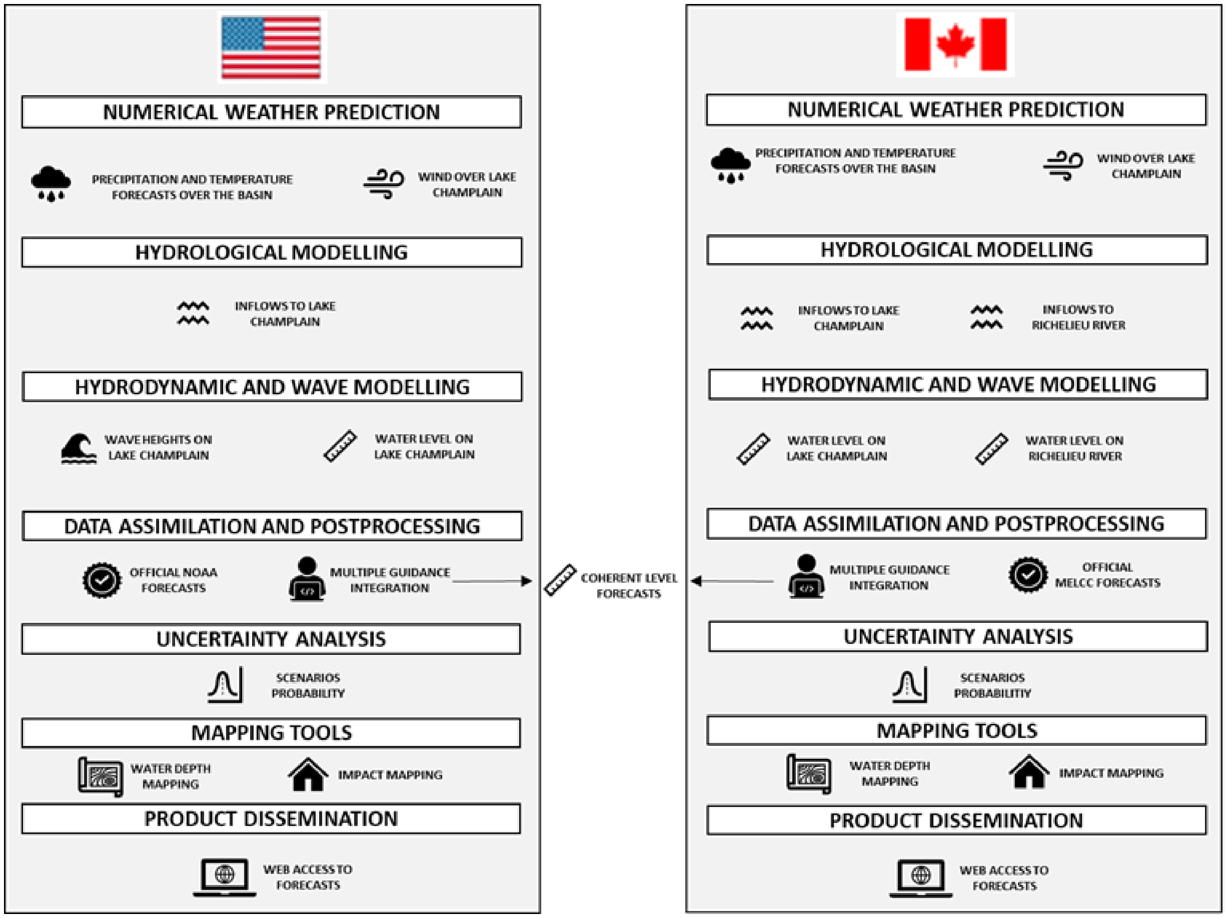


Figure 4. Recommended binational flood forecasting system.

An important aspect of this recommended system is that it is binational in the sense that its processes ensure coherence between the forecast on the US side (upstream) and the Canadian side (downstream) of the border. Both countries have responsibilities to publish forecasts on their respective territories only. However, it is important to ensure coherence with the other country's official forecasts along the border, specifically on the main scenario of the forecast, since forecasts are often given with uncertainty bands. This minimizes the risk of having contradictory messages such as (1) two different forecasts at the border (e.g., different stage predictions at Rouses Point) and (2) having a downstream location forecast inconsistent with an upstream location forecast (i.e., for stage in the Richelieu). Once a coherent set of forecasts for the LCRR system have been developed, then the products and services based upon them will also be consistent with each other (e.g., flood maps and damage assessments).

Both MELCC and NOAA forecasters should ensure binational coherence and publish official forecasts limited to their respective area of responsibility.

This does not mean that the different agencies cannot produce model guidance across the overall LCRR watershed. However, this model guidance is shared between the agencies and these are not official forecasts. It falls to the responsible agencies (NOAA and MELCC) to produce their respective official forecasts by making the best use of these multiple sources of guidance.

3.3 NUMERICAL WEATHER PREDICTION

Numerical weather prediction is the first step towards producing a flood forecast. Atmospheric models simulate various parameters of the weather processes and assimilate multiple observation sources (precipitation, temperature, pressure, etc.) to produce weather predictions.

The main forecasted variables required to produce a flood forecast are typically precipitation and temperature. However, in the case of the LCRR system, wind forecasts are also required to consider two wind effects on Lake Champlain. The first is the wind set-up (or storm surge), which is the wind pushing on the water and increasing or decreasing the water level. Since Lake Champlain is elongated along the north-south axis and its main outlet is at the north, the wind set-up affects not only the water level itself, but also the discharge of the lake to the Richelieu River if winds are aligned closely with the main axis of the lake. The second wind effect is the waves created by wind that increase nearshore water levels and cause significant damage on the lake shore.

Numerical weather prediction can be deterministic, meaning that the forecasted variables are part of a single scenario produced by the initial conditions of the simulation. Typically, a deterministic forecast is best suited for short term forecasting (a few days).

Weather forecasts can also be probabilistic, meaning that an ensemble of scenarios (called members) is produced from a set of probable initial conditions, model configurations, or different models. Ensemble weather forecasts are preferred for a state-of-the-art forecasting system, as they allow for an assessment of forecast uncertainty. They are also preferred for production of long-term flood forecasts since weather forecast uncertainty quickly increases with lead time, making deterministic forecasts less reliable. However, ensemble suites of model guidance are not yet available operationally for all variables that influence water level and coastal flood predictions in the LCRR. This study is building upon existing deterministic approaches to improve the quality of guidance available to expert forecasters.

Recommendations for the FFS include the use of deterministic forecasts for short term forecasts (a few days) and ensemble forecasts for longer term forecasts. Required variables are precipitation, temperatures and wind.

3.4 HYDROLOGICAL MODELLING

Hydrological models simulate the water cycle processes across a watershed to calculate water flows at its outlet. Running a hydrological model with weather forecasts as inputs is the main and most basic tool to produce a flood forecast across a basin. In addition to the precipitation and temperature inputs, running a hydrological model also requires the initial state[3] of the watershed. This initial state describes the current conditions on the basin such as the characteristics of snow on the ground, the soil moisture, and water running through the river network.

Different kinds of hydrological models exist and can describe the water cycle processes differently, leading to some difference in the number of state variables. However, there are two main categories of hydrological models: lumped and distributed models. Lumped hydrological models describe the catchment in a global fashion, represent the states in the catchment (e.g., snowpack, soil moisture, temperature, precipitation) as global values, and compute the water flows at the outlet only. Distributed models break down the catchment into smaller units (such as a grid), each assigned their own states and inputs. The flow and state variables are then calculated in each subunit and summed at various points in the network. Although this more detailed approach may seem like an advantage for an FFS, lumped watershed models can be used in cascade with one another to produce similar results. The individual forecasting agencies select the hydrological model best suited to their capabilities, expertise and objectives.

Specific hydrological modelling approaches or requirements in the LCRR watershed are not mandated within the study workplan, other than inclusion of snow accumulation and melt processes, which are already included for hydrological models used in Canada and the United States.

As with weather forecasts, hydrological model ensemble forecasts can also be produced, often by running simulations with multiple members of the weather ensemble forecast. Consequently, deterministic hydrological forecasts produced by single weather forecast inputs are better suited for shorter terms, whereas ensemble hydrological forecasts are more useful for longer terms.

For the LCRR FFS, hydrological modelling must include snow accumulation and melt modelling. Model simulations should be done using a deterministic weather scenario for short term forecasts (e.g. a few days) and using ensemble weather forecasts for longer terms.

Recent research in hydrological modelling, however, tends to point toward the idea that mixing predictions from different models tend to produce better results (Seiller et al 2017). This can provide an additional means of producing ensemble hydrological forecasts (i.e. mixing different hydrologic models and/or using ensemble weather forecasts). Implications for the LCRR FFS will be discussed in the Data assimilation and post-processing section below.

3.5 HYDRODYNAMIC MODELLING

Hydrodynamic modelling is a tool often used when information on the water dynamics of a lake or larger body of water is required to produce adequate flood forecasts. For instance, water flows simulated by a hydrological model are insufficient to determine lake circulation and water level variability in a lake.

Hydrodynamic models are used to predict the variability in water levels, currents, temperatures and related parameters in a body of water. Different types of hydrodynamic models exist, with varying levels of complexity, advantages and limitations. They include one-, two- and three-dimensional hydrodynamic models.

Some simple combinations of models such as rating

[3] The term “state variables” or “state” refers to a set of modeled values used to describe the current conditions on a modeled watershed such as the presence of snow on the ground, the soil moisture, the current water flow in the river network, etc.

curves and water balance models can be sufficient to convert hydrological model inflows to Lake Champlain water level forecasts and Richelieu River flow forecasts. They may have the advantages of simplicity, ease of execution, and adjustment on an operational basis. However, these models can fail to consider more complex processes such as wind and wave effects, and so require more post-processing.

Complex two- and three-dimensional hydrodynamic models use inflows as input and can simulate wind effects on water bodies such as lakes using wind forecasts as a forcing. Moreover, if they are calibrated in transient state (i.e. with time varying boundary conditions), they can also be used as water balance models.

For the LCRR, simple one-dimensional models have historically been used to produce the forecasts. Their simple nature makes it easy for the forecasters to interact with the models by adjusting inputs or parameterizations in real time to improve results. However, these models have not been able to account for the effects of wind on lake levels or the creation of wave conditions that contribute to flood damages. Forecasters are aware of the limitations of these models in day-to-day operations.

As will be presented in the next section, more complex three-dimensional models are now available following the LCRR Study. They have the advantages of addressing the missing processes (wind and wave effects) for Lake Champlain. However, this does not mean that the simpler modelling approaches currently employed should be abandoned in the recommended FFS, merely that they should be used in parallel with the newer, more complex models. This will allow real-time operational assessment of the advantages and disadvantages of modelling approaches, as well as ways for the operational forecasters to interact with the models and use their results in forecast systems.

Potential mitigation measures or operational changes need to be incorporated into hydrodynamic modelling used for forecasts. For example, if a control structure or diversion is to be employed in the LCRR system, any hydrodynamic models implemented must be able to simulate the effects of those modifications, whether through changes to model boundary conditions, alterations to the modelling domain, or inclusion of control structure management rules. The type of control structure or diversion can have significant impacts on both the long term and shorter term forecasts.

As with the hydrological modelling, production of ensemble forecasts by running hydrodynamic models with multiple inflow scenarios will ultimately help to establish ranges of uncertainty in the hydrodynamic model forecasts, particularly for longer terms (a few weeks). As computational resources become more readily available and processing speeds increase, the inclusion of ensemble hydrodynamic modelling (i.e., using different model configurations or forcings) into the operational LCRR FFS should be considered. It is important to consider that long-term uncertainties on variables such as wind can make it challenging to include this process in long term water level forecasts, even

For the LCRR FFS, a combination of simple and more complex hydrodynamic models is recommended. For the short term, wind and wave effects on Lake Champlain water levels must be included. For long term forecasts, wind and wave effect can be included pending proper skill assessments.

Structural mitigation measures should be accommodated by hydrodynamic modelling predictions. The effects of real-time modifications to the LCRR system (e.g. application of management rules, changes to boundary conditions) must be simulated within the FFS, as the operation of mitigation measures can affect water levels.

probabilistic ones.

3.6 DATA ASSIMILATION AND POST-PROCESSING

Data assimilation is the process through which a model's internal state variables are adjusted to better fit observations such as discharge or water level measurements from a gauge. Post-processing is any modification made to an output of a model with a similar goal, or to support outputs such as products or visualizations. A major distinction is that data assimilation requires running simulations of the model whereas post-processing does not.

LCRR FFS requires NOAA and MELCC forecasters to ensure coherence between the official forecasts using data assimilation, post-processing and guidance forecast integration. New methods will be developed as new models are used in operations.

Forecasters typically use a combination of both methods to produce an official published forecast. Additionally, forecasters can also integrate the results from multiple models within operational forecast systems.

It should be noted that this aspect of the FFS could be applicable to the entire forecasting chain (weather, hydrological, hydrodynamic, or wave modelling). Many data-assimilation and post-processing techniques exist and depend upon the model selected. These methods can sometimes overlap; for instance, data-assimilation can be used to integrate forecast guidance. Figure 5 provides examples of the adjustments that can be made.

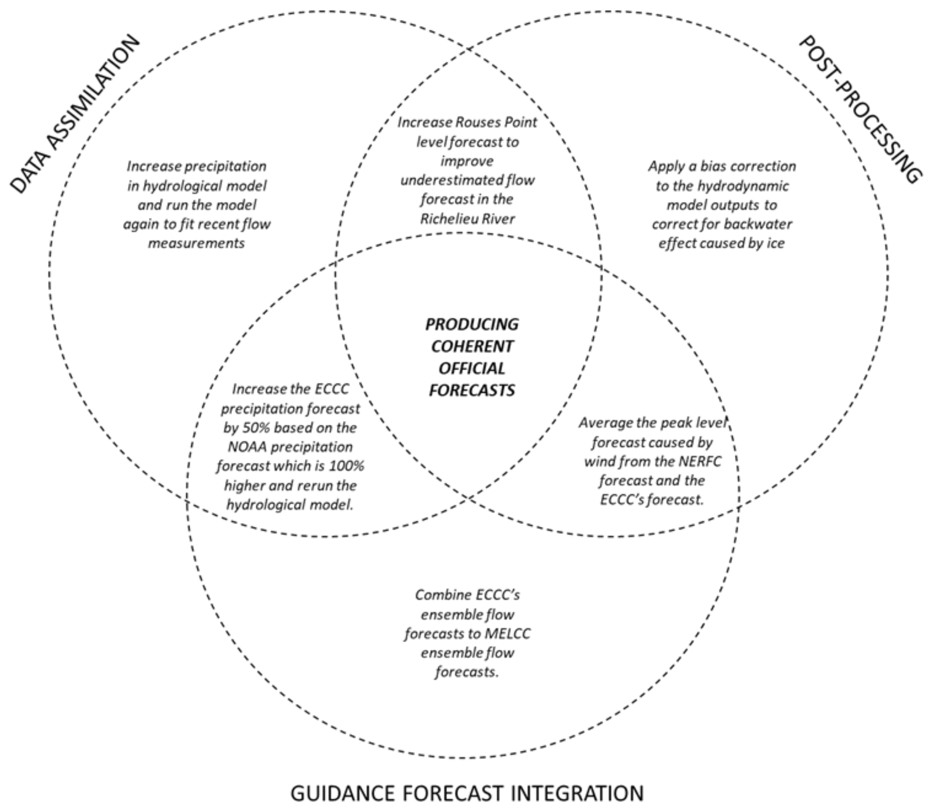


Figure 5. Integration of data and model results to produce official forecasts.

In the case of the LCRR, these methods already exist. However, additional tools and models add complexity and require further consideration by the forecasters, who ultimately have the responsibility of producing optimal forecasts.

3.7 UNCERTAINTY ANALYSIS

Uncertainty is inherent to weather and flood forecasting. For example, when considering the hydrological modelling, the main sources of uncertainty include (1) initial conditions, (2) modelling structure and resolution and (3) weather forecast uncertainty.

Initial condition uncertainty is related to the fact that it is impossible to know exactly the current state of a watershed, i.e., the flow in each tributary or river reach, the soil water content in each underground layer, the snow water equivalent (SWE) on every part of the territory, etc. In the case of the LCRR system, which has a large basin and is a slow responding system, initial condition uncertainty can have long-term impacts. For instance, uncertainty on the SWE prior to the spring melt can translate to uncertainty on the inflow forecast for the following weeks.

Modelling structure and resolution is the uncertainty related to the choice, implementation and calibration of mathematical models used to represent the hydrologic cycle process. For instance, there is more than one way to model snow accumulation/melt. Typically, more complex mathematical models require more inputs, but can capture more complex processes. Simpler models do not simulate these more complex processes, but require fewer inputs. The choice of model(s) is always a careful balance between complexity and simplicity applied to the modelling task. Moreover, the use of multiple simple models and the averaging of their output may produce better results for certain conditions because their modelling strengths tend to complement each other. Therefore, more complex models may not always be the best choice.

Weather forecast uncertainty is a direct consequence of the fact that weather forecasts become less accurate with lead time. If precipitation accumulations can be forecasted adequately for the next day, the same cannot be said for the precipitation accumulations of the fifth day. This is the main reason why ensemble weather forecasting produces more useful results for long-term forecasts. Instead of producing one scenario (deemed the most probable), it is better to produce multiple scenarios that give an idea of the uncertainty, and to express the forecast as a probability.

> For the LCRR FFS, uncertainty assessment should be available with water level and flow forecasts (short term and long term). This uncertainty could be expressed as upper and lower limits (associated with their probabilities) around a central scenario (either the median or the mode).

Multiple tools and methods exist to estimate uncertainty, from empirical models based on historical errors to ensemble forecasts. Generally, these tools and methods are used to associate a probability with an upper and lower limit to the main forecast, often the median (50% probability of exceedance). One approach, currently employed by NOAA and shown on its Advanced Hydrologic Prediction Service (AHPS) web pages, demonstrates uncertainty using the Hydrologic Ensemble Forecast System (HEFS) by showing the median probability forecast bounded by envelopes of most likely (25 – 75% probability), likely (10 – 90%), and less likely (5 – 95%) solutions. An example of this approach is shown in Figure 6 for an HEFS forecast at Essex Junction, VT.

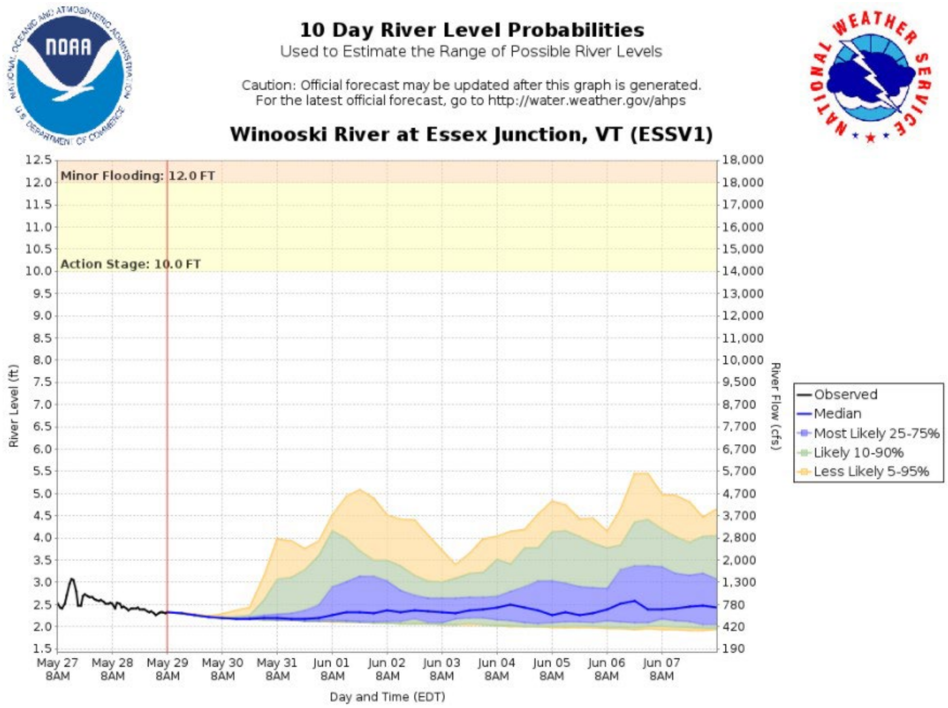


Figure 6. Example of forecast uncertainty, showing 10-day river level probabilities.

When considering hydrodynamic modelling to produce water level forecasts, additional sources of uncertainty should be considered. Of course, the uncertainty associated with the hydrological forecasts affects the result, but so does the uncertainty of the model structure and the uncertainty of additional inputs used (e.g. wind forecasts).

3.8 MAPPING TOOLS

For users in the emergency management community and the public, river/lake flow and water level forecasts can be useful but are hard to visualize as real-world impacts (for example, it can be hard to put a flow of 950 m^3/s into perspective). One possibility to address this difficulty is to associate different flows or water levels with known impacts (for example: flooding up to landmarks such as major streets). However, this association is unique for each individual location, as it is specific to the terrain configuration and the local conditions.

Flow forecasts from hydrological models can be translated to water levels using either a hydraulic (i.e., simple model of fluid properties) or hydrodynamic (i.e., more complex model of fluid motion) model. A water level forecast can be associated with a terrain elevation. This is more useful but may still be difficult to translate to a real-world situation. Additional steps can be taken to translate the water level forecasts to a map showing the area that would be underwater (i.e., inundated) for a given forecast. One can then easily visualize the impact of a certain flow or water level for a specific location of interest, and a specific duration of flood.

For the LCRR FFS, flood forecasts and their uncertainty should be made available in a map format to easily understand and visualize flood impacts. These maps should show water depth values and be associated with a probability of exceedance (uncertainty).

These mapping tools can be used not only to translate the water level forecast to an area of flooding, but also to show the flood depth given a certain water level on a map. Furthermore, it is also possible to use mapping tools to evaluate flood forecast impacts in terms of various indicators such as damages to homes or buildings ($) or disconnected road networks or number of isolated residences; these tools may be as useful in urban planning as they are in flood forecasting. While maps of flood impacts are not typically part of the forecast itself, they can be extremely useful for emergency managers, first responders and other decision makers. Examples of flood impact maps have been produced by the study for several municipalities and were presented during a workshop on user needs in February 2021.

3.9 PRODUCT DISSEMINATION

FFSs include product dissemination; in addition to locational information such as maximum forecast flows and water levels, forecast products such as graphs, maps or risk indicators need to be made available to the end users. Depending on the situation, these products can be tailored to the end-user. For instance, flood responders often need more detailed forecasting products than the public. Also, in flood situations, forecasters can provide more product context to these responders, via decision support services.

An important aspect of product dissemination is its timeliness. Forecasting products quickly become obsolete as time passes and updates are routinely made. It is imperative that the forecasting products be made available as soon as official forecasts are produced. Online dissemination thus becomes an obvious choice for product delivery.

LCRR official forecast products such as maps and graphs must be made available online to end users within a reasonable time after their production by the forecasters.

Short term forecasts (two to five days) should be detailed as graphs and maps and include some uncertainty assessment. Longer term forecasts are also needed but should be probabilistic. Their levels of detail should be coherent with the forecasting skill.

The choice of product is also important. In the case of the LCRR, a short-term forecast (few days) is important because the wind effect can quickly increase or decrease water levels. Even as wind becomes harder to forecast at longer time steps, the generally slow response of the system's mean lake level allows for meaningful longer-term forecasts that consider uncertainty. Forecasts beyond five days should most likely become probabilistic assessments, as uncertainty can become too high for a deterministic forecast to remain reliable.

4 AVAILABLE IMPROVEMENTS, GAP ANALYSIS AND ROADMAPS

4.1 CURRENT SERVICES

Although the LCRR study developed tools and models to improve the forecast and mapping capabilities, forecasting services previously existed in both Canada and the United States. The existing systems are very familiar to forecasters, who understand their strengths and weaknesses and prediction skill (i.e., accuracy at difference time scales).

Current services in Canada are described in APPENDIX F – Forecasting services and skill metrics for Canada. Current services in the United States are described in APPENDIX G – Forecasting services and skill metrics for the US. As new tools and models become available, their integration in services will allow moving forward to the recommended FFS.

4.2 AVAILABLE TOOLS AND MODELS

Conceptual requirements for the LCRR FFS can be compared to the current set of models and tools available. Some tools were already in operation prior to the current study. Others were identified as tasks, funded and developed during the span of the study. Finally, some other models and/or tools were developed during the study, but were outside of its scope and funded by other initiatives. Figure 7 presents these various tools for the province of Québec and for the United States that can ultimately be part of the recommended FFS. For weather, hydrological, and hydrodynamic models, the area modelled is also presented. The term "in operation" means that the model is currently producing results daily. A model's development can be completed but without being integrated in a forecasting infrastructure to produce daily results.

In the following sub-sections, an overview of these various tools and models is given as well as references to more technical details available, when applicable.

4.2.1 Numerical weather prediction at ECCC

ECCC issues weather forecasts over all of North America for lead times of one hour to one month using two Global Environmental Multi-scale (GEM) atmospheric models: the Global Deterministic Prediction System (GDPS) and Regional Deterministic Prediction System (RDPS). More generally, the GEM model is very flexible: the domain, horizontal resolution and forecast horizon (lead time) can be configured based on user needs and available computer resources. GEM can also be two-way coupled to hydrological models and ocean models. As such, two ensemble configurations of the GDPS and RDPS exist and operationally produce probabilistic forecasts of weather variables: the Global Ensemble Prediction System (GEPS) and Regional Ensemble Prediction System (REPS). More technical details can be found in APPENDIX B - ECCC weather forecast model configuration and skill metrics.

4.2.2 Numerical weather prediction at NOAA

NOAA's Weather Prediction Center (WPC) issues forecasts for North America four times daily; these are interpreted and augmented for local regions by Weather Forecast Offices. These forecasts are informed by multiple atmospheric models, including the Global Forecast System (GFS), the North American Mesoscale (NAM) forecast system, the European Centre for Medium-Range Weather Forecasts (ECMWF) global model, the High-Resolution Rapid Refresh (HRRR) model, and the National Blend of Models (NBM), among others.

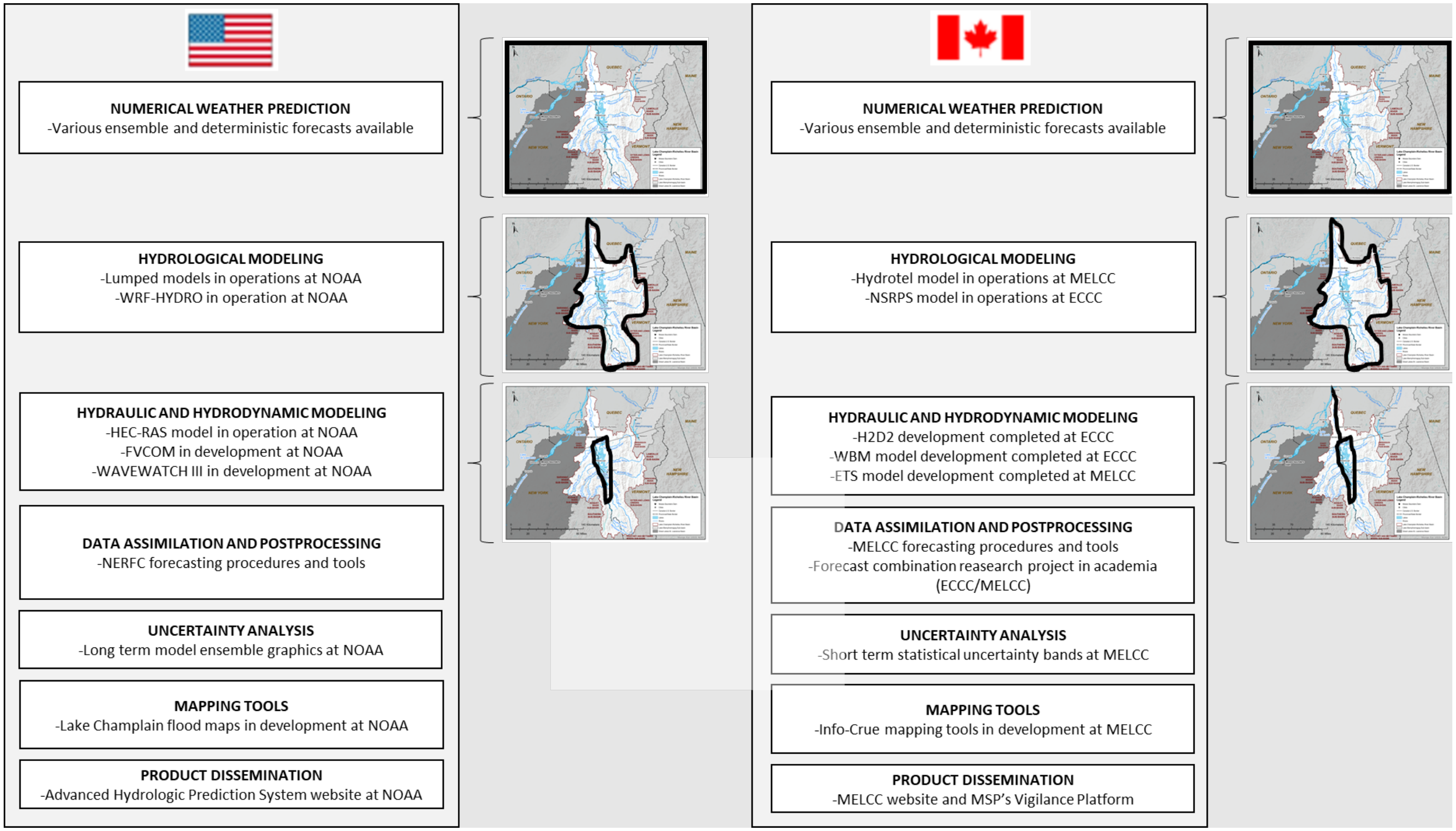


Figure 7. Potential tools and models to be included in the recommended LCRR flood forecasting system.

Each of the atmospheric models that WPC considers when developing their forecast is available at different spatial resolutions and time horizons. More technical details can be found in APPENDIX C - NOAA weather forecast model configuration.

4.2.3 MELCC's hydrological model: Hydrotel

Hydrotel is the main hydrological model used by the MELCC forecasting team. It is a semi-distributed model developed by INRS-ETE that is deployed for every forecasting location within the province of Québec. At gauged locations, forecasters produce a forecast by completing manual assimilations of discharge with Hydrotel and selecting the numerical weather forecast guidance such as combined RDPS-GDPS or combined NAM-GFS. They also use ensemble guidance to assess the potential variability in the forecast.

In addition to being deployed for each gauged location, an ungauged locations version has also been deployed on the whole domain of southern Québec, as shown in Figure 8.

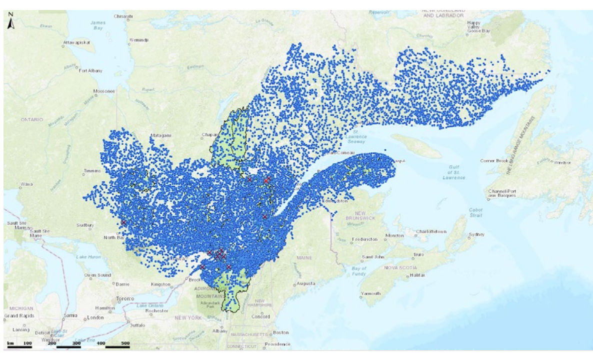


Figure 8. Global Hydrotel implementation on southern Québec.

This implementation is used to produce discharge values for every catchment up to a certain resolution (approximately 25 km^2). Using an interpolation method (Lachance-Cloutier et al. 2017), output of this global platform is combined with the official forecast produced by the forecasters at gauged locations to produce discharge forecasts for the whole of southern Québec.

Currently, this method does not include forecasts from the NERFC's domain and so is not used to produce water level forecasts at Rouses Point. Instead, MELCC directly converts the NERFC forecast for this location into discharge from Lake Champlain into the Richelieu, adding inflows along the river to produce a complete forecast.

4.2.4 ECCC's hydrological model: National Surface and River Prediction System (NSRPS)

The experimental National Surface and River Prediction System (NSRPS) was put in operation at ECCC in March 2019. This deterministic prediction system relies on the hydrological Global Environmental Multi-scale model (GEM-Hydro; Gaborit et al. 2017) to provide forecasts of the state of the land surface and rivers. Deterministic forecasts produced twice each day (00 UTC and 12 UTC) are available for lead times up to six days. Surface and near-surface variables are simulated at a 2.5-km resolution, while the hydrological components are resolved at a 1-km resolution over six major Canadian basins, including the LCRR watershed. At present, the system is forced with the atmospheric predictions produced by the GEPS and REPS. Relying on the Canadian Precipitation Analysis (CaPA; Fortin et al., 2018) and Canadian Land Data Assimilation System for Satellite Data (CaLDAS-Sat; Carrera et al., 2015), the NSRPS assimilates precipitation, soil moisture, surface humidity and temperature observations. CaPA (Fortin et al., 2018) is responsible for estimating the precipitation that reached the ground since the last forecast was launched, based on information provided by in-situ data, satellite data and ground radar, as well as a short-range RDPS forecast. CaLDAS is responsible for estimating the soil moisture, soil temperature and snow cover based on in-situ and satellite data. The observations assimilated by CaPA and CaLDAS are then used to produce analyses and forecasts of surface variables through the High-Resolution Deterministic Land Prediction System (HRDLPS). Finally, the Deterministic Hydrological Prediction System (DHPS) component assimilates discharge observations at available gauges, estimates the storage of water in rivers and shallow aquifers (during the assimilation cycle) and implements the river flow routing and forecasting (during the forecast cycle). NSRPS provides forecasts for all tributaries of LCRR but is not coupled with the atmospheric and ocean models. Hence, while integrating the water balance model to estimate the Saint-Jean-sur-Richelieu level from Lake Champlain levels, it does not account for wind effects and direct precipitation/evaporation on the lake.

Since spring 2020, an experimental NSRPS version has produced ensemble hydrological forecasts by coupling the ensemble adaptations of the weather, surface, and hydrological system components: the GEPS and REPS, HRELPS, and EHPS forecasting systems (the "E" letter stands for Ensemble instead of the former "D" letter for the Deterministic versions). Specifically, the EHPS presently provides daily ensemble forecasts (20 members + 1 control) at 00 UTC with a 16-day forecast horizon and weekly discharge forecasts for lead times up to 32 days7. Tributary flow, precipitation, evaporation, and wind outputs from the ensemble NSRPS are used as inputs for the H2D2 hydraulic model, to produce a hydrodynamic forecast model of the LCRR. More details can be found in APPENDIX D – NSRPS model technical details.

4.2.5 U.S. Distributed Hydrologic Model: WRF-Hydro

Improvements to flood forecasting in Lake Champlain and the Richelieu River will depend on improving the accuracy of water level predictions in the lake and river. Presently, hydrologic forecasts of river levels are made for select watersheds at forecast points where USGS gauges have been located and rating curves established. However, this leaves more than 30 percent of the inflow (from ungauged areas) around Lake Champlain unaccounted for. Because of the limited coverage and relatively small number of forecast locations with these lumped hydrologic models, the NWS has implemented a new high resolution distributed hydrologic model. The National Water Model (NWM) greatly increases the number of river forecast locations by resolving US watersheds with a 1 km resolution land surface model along with a 250 m stream network to hydraulically route water through streams and rivers. The NWM provides forecast guidance in a number of ways, as shown in Figure 9 (NOAA NWS Office of Water Prediction, 2019).

Figure 9. Configuration of the National Water Model (from NOAA Office of Water Prediction; accessed October 20, 2019).

The NWM is presently operational within the NWS, but has not been calibrated for all areas. Therefore, this project is improving the NWM in the Lake Champlain basin by calibrating against local observations to provide accurate inflow predictions into the lake, as well as improve forecasts on all streams in the basin. A high-quality hydrofabric (i.e., a spatial dataset which includes the stream and reservoir network, channel geometry, roughness, and topography) was developed for the basin which improved stream routing networks and incorporated recent topographic data. This hydrofabric has been calibrated against historical data and was integrated into version 2.1 of the NWM in 2021.

4.2.6 ECCC's water level component: Water Balance Model (WBM)

ECCC's Water Balance Model serves as a simpler alternative (compared to the H2D2 hydraulic model described below) to converting inflows and current level of Lake Champlain to outflows through the Richelieu River. In an operational context where forecasters monitor and correct biases daily, this kind of tool can be used quickly and with multiple guidances (i.e., inflows). Moreover, any modification required to follow management decisions on a control structure can be quickly adjusted. WBM does not consider wind effect but can be coupled with the ETS model (described later in this report) to provide discharge forecasts in the Richelieu River.

This model is based on the conservation of mass equation. Detailed equations can be found in APPENDIX E – Detailed equations and operation of the water balance model.

4.2.7 ECCC's Water level component: H2D2

The study employed the hydrodynamic model developed earlier in 2015 as part of the demonstration of an operational forecasting toolkit by the International Lake Champlain – Richelieu River Technical Working Group (Boudreau et al. 2015a, 2015b). The task group produced flood maps for various flow and water level scenarios from Rouses Point as a point on Lake Champlain to Fryer Island Dam downstream of this point. The downstream limit for the initial study was dictated by the quality of bathymetric data. Once better bathymetry became available north of the Fryer Island Dam, the model was extended to its downstream boundary at Sorel.

The hydrodynamics of the system were represented by a two-dimensional hydraulic model, H2D2, developed at INRS-ETEwith the assistance of ECCC. The model solves the Navier-Stokes (Saint-Venant) two-dimensional long-wave equations. Like all two-dimensional models, H2D2 uses depth integrated information and only allows variation in the cartesian x and y directions. More details on the model can be found in the H2D2 standalone report of the IJC LCRR study.

4.2.8 U.S. Lake Champlain Hydrodynamic Model: FVCOM

Forecasts of Lake Champlain water levels have had difficulty accounting for wind effects. This is because NOAA's existing forecast model for the lake is a relatively simple one-dimensional HEC-RAS hydraulic model. This version of HEC-RAS is designed to calculate the flow of water through rivers and channels based upon cross-section profiles and hydrologic inflows, but cannot account for wind effects on water levels. The basic computational procedure for the Lake Champlain HEC-RAS application calculates unsteady-state flow, producing a one-dimensional profile of the water surface along its course. However, water levels within Lake Champlain, which drive Richelieu River levels and flooding conditions, are not only affected by hydrologic inflows but also by winds and waves. Wind across the surface of Lake Champlain drives water up against the shoreline (i.e., storm surges) and generates large waves. Water level differences of several feet can exist between opposite ends of the lake during strong wind events, with wind wave heights reaching up to five feet occurring coincidentally with these water levels. Seiches also result from winds closely aligned with the north/south axis of the lake, causing large surges which then oscillate back and forth from one end of the lake to the other. If these conditions occur when lake levels are already high (due to a significant volume of inflow to the lake), significant shoreline damage can occur, and high-water levels can propagate downstream along the Richelieu. Additionally, winter lake ice conditions can also affect shoreline and flood conditions; ice alters the effect of wind blowing across the lake, and shore-fast ice can provide protection from wave conditions.

To improve flood forecasting in Lake Champlain, NOAA has developed a new forecast guidance model for the lake. First, a three-dimensional hydrodynamic circulation model has been developed. This model, an application of the Finite Volume Community Ocean Model (FVCOM), will generate three-dimensional predictions of lake levels, currents, and temperatures. With a spatial resolution of several hundred meters, five-day lake predictions will be created four times per day. Driven by river inflows and meteorological forecast guidance, this model will predict changes in lake conditions caused not only by river inflows, but also wind, air pressure, and air temperature.

4.2.9 U.S. Lake Champlain Wave Model: WAVEWATCH III

In addition to the FVCOM development, the wave modelling system used in the Great Lakes has been expanded to include Lake Champlain to predict wind wave conditions on the lake, which can have a significant impact on lakeshore flooding. This system, an implementation of the WAVEWATCH III® model, will be executed on an hourly basis and provide forecasters with 5-day predictions of significant wave height and peak wave direction. The wave model uses the same grid as the Lake Champlain FVCOM model grid, is driven by the same meteorological forcings as the hydrodynamic model, and uses water level predictions from FVCOM as input which will affect wave conditions. With these wave predictions, forecasters can convey wave impacts on lake shorelines including the additional damage and flooding that could be caused by wave run-up.

4.2.10 ETS MODEL

The ETS model is a post-processing model specifically designed to forecast the water level increase at Rouses Point caused by wind that can affect the forecasts. It has been developed by l'École de Technologie Supérieure (ETS) within the LCRR study in order to provide a simple tool to forecast wind set-up at Rouses Point. The model uses wind speed and direction across the Lake, as well as wind gusts and atmospheric pressure difference between both ends of the Lake as inputs. This model could be used to account for wind effect in situations when NOAA's forecast does not account for it or when using other level forecasts, for instance from the water balance model.

Three different wind setup models were tested, (designated A, A modified and B) as shown in Figure 10. In the end, the model B was selected to become the ETS model. Model A uses wind speed and direction at a single point on the lake as inputs. Modified model A sees a constant added to correct a bias produced by static level variation between the northern and southern tip of the lake. Finally, model B was developed by ETC to use model A inputs on more than one location, as well as considering wind gust as an additional input.

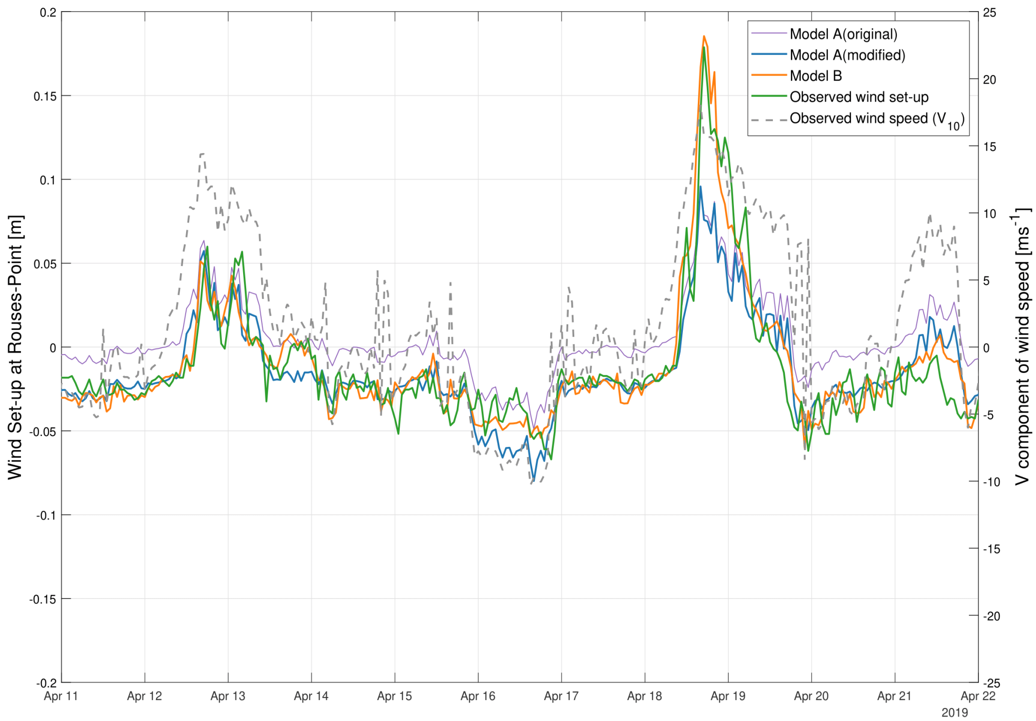


Figure 10. Comparison of the different wind set-up models.[4]

4.2.11 Info-Crue mapping tools and product dissemination at MELCC

The development of a cartographic and information dissemination tool requires a thorough collaboration with organizations or ministries having jurisdiction over the dissemination of information relating to the impacts of floods and public safety (i.e., MSP in Québec). The Info-Crue[5] project is intended to develop and consolidate knowledge on the evolution of areas at risk of flooding, and make cartographic information available for decision-making. Within the Info-Crue project, and in collaboration with MSP, MELCC will be producing flood map forecasts, i.e., maps of the predicted flood extent for the following days. The final design of such a product is not yet complete, but ongoing consultation is currently being carried out by Université du Québec è Rimouski within a research project.

During the spring of 2021, the Info-Crue product was tested within the MSP's Vigilance platform with access restricted to MSP's personnel. It provided forecasts for the maximum reach for the first and second day of the forecast horizon. Two scenarios were made available, the median scenario and a high scenario corresponding to the 75% probability of non-exceedance. One map is created per forecast day which illustrates the flood depth reached at the maximum flow of the day. Figure 11 provides an example of the current design of the Info-Crue product.

[4] Improved wind set-up model for flood forecasting on Lake Champlain, 2020 – Loiselle et al, pending publication
[5] https://www.cehq.gouv.qc.ca/zones-inond/info-crue/index.htm

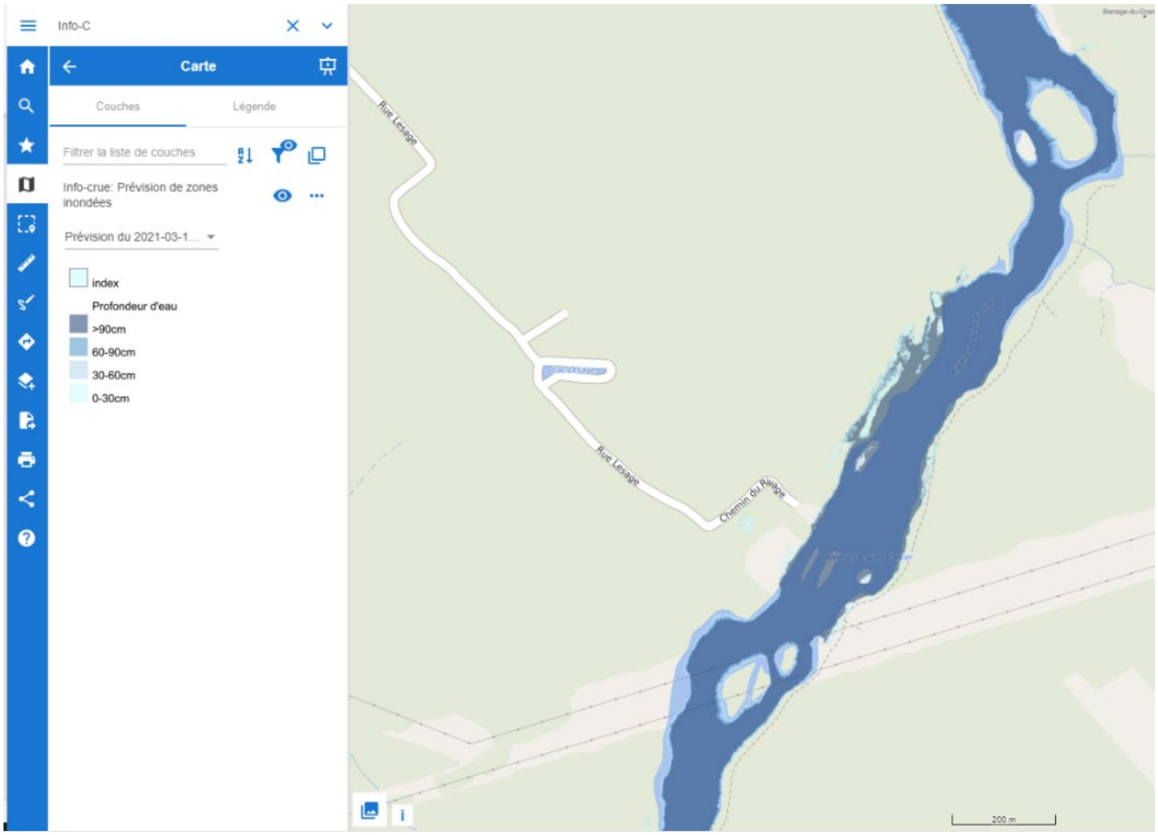


Figure 11. Info-Crue product example for the Jacques-Cartier River, Québec (French only).

The LCRR system will not be covered within the Info-Crue product in 2021. However, results from the hydrodynamic modelling efforts developed within this study by HHM (i.e., the model) are being provided to MELCC to work on deploying the Info-Crue tool on the Richelieu River itself. MELCC will then combine modelling of other tributaries included in the project. This new flood mapping product will be deployed gradually on different rivers (including the Richelieu) within the province of Québec and completed by 2023.

It is important to note that the Info-Crue project will convey uncertainty assessments and will be probabilistic in nature. This means that more than one scenario (currently two) will be available for mapping purposes, each associated with a probability.

A research project is currently ongoing with the Université du Québec à Rimouski for a major consultation of agencies, municipalities and citizen-level groups to determine the best way to present the information.

4.2.12 Mapping tools and product dissemination at NOAA

In addition to improved model guidance for flooding, new flood products can be developed. NOAA/NWS currently provides the capability to host static flood inundation maps through its AHPS web pages (https://water.weather.gov/ahps/inundation.php). NWS created a standardized process for creating flood inundation maps (Dewberry, 2011) that the USGS used for Lake Champlain, as part of previously funded IJC work (Flynn & Hayes, 2019). During that study, static flood-inundation boundary extents were created for 11 discrete Lake Champlain flood levels along the lake shoreline in Franklin, Chittenden, Addison, Rutland, and Grand Isle Counties in Vermont, and Clinton, Essex, and Washington Counties in New York. The resulting flood inundation maps may be referenced to any of the four active USGS lake gages on Lake Champlain (USGS lake gage 04295000, Richelieu River (Lake Champlain) at Rouses Point, NY; USGS lake gage 04294500, Lake Champlain at Burlington, VT.; USGS lake gage 04279085, Lake Champlain north of Whitehall, NY; and USGS lake gage 04294413, Lake Champlain at Port Henry, NY). The Lake Champlain flood inundation maps were also added to the USGS online, national Flood Inundation Mapper (FIM; https://fim.wim.usgs.gov/fim/).

The FIM allows users to explore the set of inundation maps that show where flooding would occur given a selected stream condition. The USGS FIM helps communities visualize potential flooding scenarios, identify areas and resources that may be at risk, and enhance their local response effort during a flooding event. Additional work will need to be done to transition these inundation maps to the NOAA AHPS service, ensure they are referenced to the appropriate vertical datum, and incorporate them into the NWS web services.

Figure 12 shows an AHPS inundation mapping site already available in Waterbury, Vermont based upon work done outside this study. The AHPS site displays static maps of inundation levels for a specified reach of the river (the Winooski River in this case). The user can select between displays of various inundation levels, flood categories (i.e., Minor, Moderate, Major), and the current or forecasted river levels.

The NWS Office of Water Prediction (OWP) has also developed a dynamic flood mapping approach based upon the NWM, using the Height Above Nearest Drainage (HAND) methodology. This technique has been applied for all NWM riverine locations in the conterminous United States and Alaska and has leveraged the NWM upgrades that this study made for the LCRR basin. The HAND methodology creates maps of the maximum forecast inundation extent for flood waters in the basin. However, the NWM does not currently incorporate water level predictions provided by lake or coastal models such as the Lake Champlain FVCOM model from this project. Future developments in model coupling will be necessary to incorporate hydrodynamic water level and wind wave predictions into the dynamic flood mapping approach developed by the NWS. Until those model couplings are established, the previously discussed approach utilizing the static Lake Champlain inundation maps will be in place for the discrete gauged locations along the lake shore.

4.3 GAP ANALYSIS AND ACTIONS NEEDED

Given the requirements, existing models, models in development, and current services and capabilities presented above, it is possible to analyse the gaps between the current situation and the recommended FFS. Table 1 presents this analysis, showing the actions planned and needed to complete the recommended FFS.

4.3.1 Technical barriers

Since most of the modelling tools needed to meet the requirements of the recommended FFS were pre-existing or developed during the study, there are no major technical barriers to completing model development. However, bringing these models into operations requires extensive planning and technical work that can be as important as the development of the models themselves and should not be taken lightly.

Moreover, bringing new models into operations often requires evaluating their performance in comparison to what is already in use. Some technical issues are often only noticeable in a daily operational context.

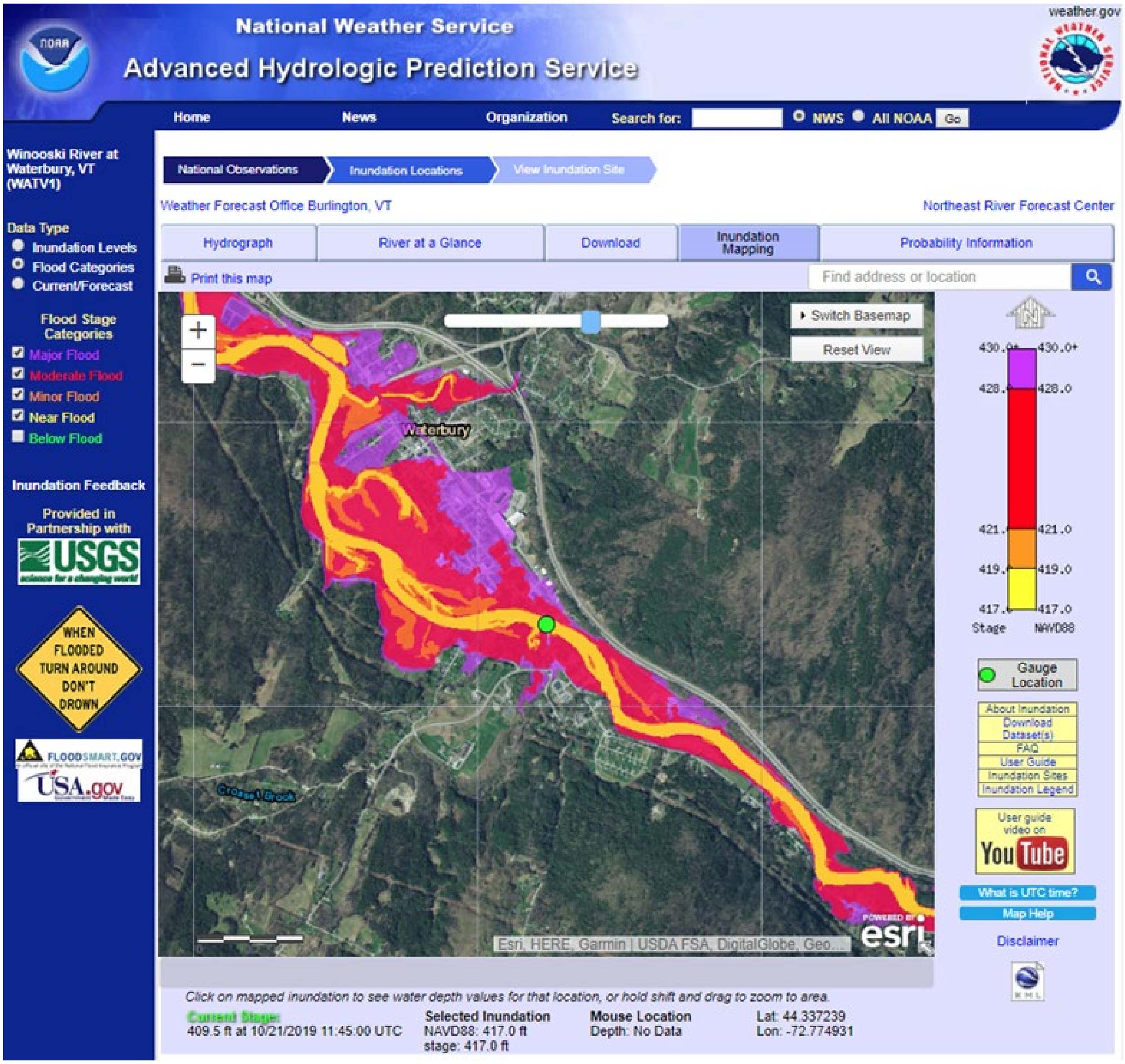


Figure 12. NWS AHPS static flood inundation mapping for the Winooski River in Waterbury, VT.

Table 1. FFS Requirements gap analysis.

REQUIREMENT	GAP ANALYSIS	ACTION NEEDED
Both MELCC and NOAA forecasters must ensure **binational coherence** and publish official forecasts limited to their **respective territory**.	No gap	None
Use of **deterministic weather forecasts** for short term forecasts (a few days) and **ensemble weather forecast** for longer term forecasts. Required variables are precipitation, temperature, and wind.	No gap	None
Hydrological modelling must include snow accumulation and melt modelling. Model simulations can be done using a **deterministic** weather scenario for short term forecasts (a few days) due to the narrow divergence in weather forecasters, and **ensemble** weather forecasts for longer term forecasts with large uncertainty in weather conditions.	-Hydrological modelling in Canada using long term ensemble weather forecasts is limited. -Snow accumulation/ ablation algorithms are in place for both existing lumped watershed models and NWM (WRF-Hydro). NWM algorithms continue to be adjusted to improve results. Current HEFS ensemble forecasts are available daily. WRF-Hydro long term (30 day) simulations are run with 16 ensemble members (4 per each 6-hour time interval).	-MELCC should run Hydrotel using long term ensemble weather forecasts on the LCRR domain. Currently, Hydrotel is only running using short term deterministic weather forecasts. -ECCC should continue moving NSRPS from an experimental status to an operational status using long term ensemble weather forecasts on the LCRR domain. Currently NSRPS do not produce ensemble forecasts. -NOAA National Water Center should continue to update NWM (WRF-Hydro) snow accumulation/ablation algorithms to improve hydrologic forecasts.
Combination of **simple and complex hydrodynamic models** is recommended. For the short term, wind and wave effects must be included. For long term forecasts, wind and wave effects can be included pending proper skill assessments.	-Although models are available, no hydrodynamic model in Canada is currently running over LCRR. -Both hydrodynamic and wind/wave models running in experimental mode (I.e. not on operational hardware platforms).	-MELCC should deploy the water balance model to operation and use it with deterministic and ensemble inflows from Hydrotel and NSRPS. Management rules and scenario creation should be deployed if a derivation is implemented.

REQUIREMENT	GAP ANALYSIS	ACTION NEEDED
Structural mitigation measures should be accommodated by hydrodynamic modelling. The effects of real-time modifications to the LCRR system (e.g. application of **Management rules**, changes to boundary conditions) must be simulated within the FFS.	-Mitigation measures or implemented management rules would result in changes to projected Richelieu River flows, which would then be incorporated into the downstream boundary for the FVCOM model.	-ECCC should run the H2D2 model using NSRPS ensemble forcing and ensemble wind forecast and provide forecast guidance to MELCC for integration. H2D2 model should include management rules if a derivation is implemented. -NOAA will need to execute a transition to Operations to move the FVCOM and WAVEWATCH III models from their current remote standalone platforms to the operational platform (on the NCEP WCOSS supercomputer)
NOAA and MELCC forecasters must ensure coherence between the official forecasts using **data assimilation, post-processing and guidance forecast integration**. New methods will have to be developed as new models are used in operations.	-Only manual integration of guidance forecasts is currently possible to produce official forecasts in MELCC. -Wind effect post-processing must also be done manually at MELCC.	-MELCC and ECCC should continue research collaboration to develop more formal forecast guidance integration that includes uncertainty assessment. -MELCC should implement the ETS model in its operation. -NOAA and MELCC should continue existing forecast collaboration and ensure seamless transition to newer models.
Uncertainty assessment should be available with water level and flow forecasts (short term and long term). This uncertainty should be expressed as an **upper and lower limit** (associated with the probability of each) around a **central scenario** (either the median or the mode).	-MELCC official forecasts already include uncertainty, but the method is not suited to ensemble forecasting and guidance forecast integration. -NOAA currently provides uncertainty assessments (via HEFS) as stipulated for lumped and hydraulic model forecast points. Future assessments of uncertainty for hydrodynamically modeled forecast points will be dependent on the availability of hardware resources (for conduct of multiple ensemble member runs).	-MELCC and ECCC should continue research collaboration to develop more formal forecast guidance integration that includes uncertainty assessment. -NOAA should continue to monitor progress of hardware resource availability and advancement of processing speeds that can accommodate multiple hydrodynamic model runs for eventual execution of hydrodynamic ensembles.

REQUIREMENT	GAP ANALYSIS	ACTION NEEDED
Flood forecasts, and their uncertainty should be made available in a **map format** to be easily understood and visualized. These maps should show **water depth values** and be associated with a **probability of exceedance** (uncertainty). Flood impact maps could be used inside or outside the FFS depending on their use.	-Only static inundation maps at 11 discrete water surface elevations have been developed for both Canadian and US portions of the LCRR basin. -No additional flood forecast maps are currently available in Canada. -The NOAA National Water Center produces inundation maps for flood waters using the NWM (WRF-Hydro) but does not yet produce these maps from water surface elevations forecast by other external models (e.g., FVCOM). -No additional flood forecast maps are currently available in the US.	-MELCC should deploy Info-Crue mapping tools on the Richelieu River. -NOAA should produce inundation maps by linking forecasted lake levels to static inundation extents developed prior to the Study by the IJC. -NOAA should continue investigations into the use of the NWM hydrofabric along with water surface elevations from external models (e.g. FVCOM) for application of the HAND methodology to predict inundation extents.
Products such as maps and graphs must be made **available to end users through the web** in concert with the forecast. **Short term forecasts (2 to 5 days) should be detailed as graphs and maps and include uncertainty assessments** (i.e., probability associated with the main scenario, upper and lower limit). **Longer term forecasts are needed but should be probabilistic.** Their level of detail should be coherent with the forecasting skill.	-No long-term probabilistic forecast is currently available in Canada -For Rouses Point, NY in the US, only 10-day HEFS forecasts and 90-day exceedance probability forecasts are currently available. These forecasts are generated using the current Lake Champlain HEC-RAS model. -No long-term probabilistic forecasts are currently available using hydrodynamic models for Lake Champlain.	-MELCC should provide probabilistic long-term forecasts using forecast guidance integration of NSRPS-H2D2, Hydrotel-WBM and NOAA long term forecasts. -NOAA should continue to monitor progress of hardware resource availability and advancement of processing speeds that can accommodate multiple hydrodynamic model runs for eventual execution of hydrodynamic ensembles.
Both MELCC and NOAA forecasters must ensure **binational coherence** and publish official forecasts limited to their **respective territory**.	No gap	None

Finally, some additional research might still be required to address multiple forecast guidance integration. Some ECCC/MELCC collaboration with academia is already in progress. However, as it is a relatively new aspect of operational flood forecasting, it is important that research continues to ensure good scientific foundations.

4.3.2 Institutional barriers

Although no major technical barriers prevent the actions needed to close the gaps between the current and recommended FFS, institutional constraints can require additional steps.

As mentioned earlier, since flood forecasting is a federal mandate in the United States, NOAA employs a very structured national system with a formal review and approval process. On the other side of the border, the MELCC forecasting team is more autonomous for the province, but even backed by ECCC collaborations, is limited in its deployment capacities, as it need to support daily operations, system maintenance and R&D projects at the same time.

Strictly speaking, the recommended FFS can be attained, but it is hard to provide an estimated completion date. This is because the various agencies (MELCC, ECCC and NOAA) all require fitting the various required actions within their own plans, projects and operational constraints. It is expected to take years before all of the necessary steps to transition modelling and product upgrades are finalized; however, some project improvements are already operational, and most are available via experimental platforms.

One pathway to coordinate improvements to national, federal government forecasting capabilities is via the bilateral agreement between NOAA and ECCC. This bilateral agreement is a mechanism by which the respective federal weather agencies coordinate observing and forecasting activities that cross borders and are mutually beneficial. Recommendations to national modelling and forecasting systems, including flood products and services, that are made by the ILCRR Study Board can utilize this agreement to coordinate and jointly improve the systems that affect Lake Champlain flood forecasting. The use of the bilateral agency agreement could provide the pathway for the advancement of national-level systems to issue binational, or at least related, probabilistic streamflow model guidance, as one example.

5 GOVERNANCE OF THE LCRR FLOOD FORECASTING SYSTEM

The binational nature of the forecasting system does not require a special governance mechanism other than the existing collaboration between MELCC and NERFC. Both agencies provide forecasts for different locations and make sure they are coherent with one another. The flood forecasting system, on the Canadian side, would be operated within various organizational infrastructures (some models running within ECCC, some within MELCC), but ultimately the MELCC's forecasters would validate the official forecast.

In the United States, the flood forecasting system models would be operated at the NERFC and at the NWS National Center for Environmental Prediction (NCEP), with forecasts made jointly by the NERFC and the WFO in Burlington, Vermont. Tributary lumped watershed models will continue to be executed at NERFC, informed by National Water Model output from NCEP. The FVCOM and WAVEWATCH III modelling components of the flood forecast system will be executed at NCEP, with output for explicit forecast locations (including Rouses Point, New York) provided to the NERFC forecasting environment. Ultimately, NERFC forecasters would validate the official Rouses Point forecast.

A flood mitigation system (e.g., diversion) could be operated based upon the forecast. However, if management orders would be based on observations, forecasts would not be required. In that case, the manager would use the official forecast as a guide to plan future operations.

On the forecasting side, forecast guidance exchange would need to be automatically provided daily. In Québec, MELCC would require NSRPS and H2D2 operational run data transfer from Maestro to SPH. In the United States, transfer of atmospheric model forcing data for tributary watershed simulations will continue as presently implemented at NERFC. Transfer of atmospheric model forcing data (precipitation, temperature, wind) for FVCOM and WAVEWATCH III models will occur within the NCEP supercomputer modelling environment.

On the management side, in Canada, managers of a diversion would be required to participate in OSCQ (provincial security organization) and ORSC (regional security organization) conference calls prior to and during high flow events, as other dam managers are. Direct daily exchange would also be required between MELCC's forecasters and diversion managers to ensure coherence of the forecast with the management decisions during high flow events. In the United States, there are no managed structures on Lake Champlain. Emergency management participation for high flow events will remain as presently defined with emergency management agencies from the State of Vermont and the counties of Clinton, Essex, and Washington in New York State.

The forecasts within each country are products of the government, produced under institutions unique to each country. The institutional context for each government is briefly described below in Section 5.1. The relationship between the forecasts in the two countries is shaped according to international governance. Three options for the international governance are provided in section 5.2 for the consideration of the ILCRR Study Board.

5.1 NATIONAL GOVERNANCE OF THE LAKE CHAMPLAIN-RICHELIEU RIVER FORECASTS

The Lake Champlain water level forecasts are made by the NWS, part of NOAA. The mapping of forecasted flooded areas around Lake Champlain will be done using maps already developed by the USGS. The experimental water level forecast models developed at NOAA and demonstrated as part of this study must be integrated into the NWS forecasting system, which is expected to take place in a series of steps to be completed by 2024.

In Canada, flood forecasting is a provincial responsibility. In Québec, MELCC is responsible for producing the forecast. MELCC is already producing water level forecasts on the Richelieu River in addition to discharge values. MELCC will work collaboratively with ECCC in the delivery of flood forecasts in order to achieve the improvements recommended by this report

5.2 INTERNATIONAL GOVERNANCE CONSIDERATIONS AND OPTIONS

There are a range of options for governing the proposed binational flood forecast and distribution of products. They vary from informal arrangements with some limited interactions to a very structured, fully coordinated governance model that produces a joint, common forecast. These types of governance models have been applied to similar systems along the US/Canadian border, such as the joint management of flow over the Niagara Falls. The selection of a governance model ultimately depends on the need and the willingness of the two countries to collaborate on managing LCRR water levels moving forward.

The options presented primarily focus on bilateral arrangements between the flood forecasting agencies. The ILCRR Study Board is also exploring broader governance models in the basin, such as the establishment of an IJC Board, or pending inclusion of a water quality mandate, possibly an IJC Watershed Board. If implemented, this could add another dimension to the reporting of flood forecasting information in this binational basin.

5.2.1 Option 1: Flood Forecast Informal Sharing Governance Model

This arrangement has the least level of commitment in terms of collaboration. It involves some limited dialogue to share data and knowledge, but the onus is on the agencies to determine how, or if, coordination will occur that will result in any modifications to their respective forecasts. This is the current arrangement and primarily involves just sharing of data (e.g., water level data and forecasts at Rouses Point), especially during high water conditions. Over the last ten years, this model performed well due to the effective collaboration between forecasters on each side of the border. Because of operational forecasting mandates in the laws on each side of the border, this option is highly likely to be viable for a long time going forward as it is in best interest of each region to continue to provide flood forecasts.

5.2.2 Option 2: Coordinated Flood Forecast Governance Model

This next arrangement involves an ongoing level of coordination and dialogue, and therefore more organizational commitment. Each country maintains its own forecasting system and products, but coordinates each forecast; this can improve the accuracy of predictions due to sharing of data. This model enables the two countries to continue using their different measurement systems and language requirements. This model is being used effectively in the Great Lakes-St. Lawrence system for water level forecasting and reporting and is a comparable example for the LCRR. It is managed through a binational Coordinating Committee that meets twice annually; further description can be found at http://www.greatlakescc.org/wp36/home/about_us/ . However, Great Lakes water level forecasting occurs on much longer time scales (i.e., monthly to seasonal) than weather and flood forecasting (which is updated every six hours). There is no clear indication on whether this model would perform better than Option 1 at ensuring coherence between the forecasts, as no significant shortcomings were identified with the current model. However, this model adds more coordination burdens. Ultimately, the responsibility still falls on NOAA and MELCC forecasters to produce and issue the official forecast, as defined by law.

5.2.3 Option 3: Joint Flood Forecast Governance Model

This governance model requires a high level of commitment and coordination. It involves agreement on the binational flood forecast. The reporting would still be done separately due to measurement systems and language differences. This option would require a formal governance structure be put in place. This model could also focus on producing a joint ensemble forecast rather than trying to ensure one common agreed upon forecast, which would be less onerous. Implementation of such a model would be ground-breaking for the US/Canadian border but comes with many challenges. First, such a model is a major change from the current model. Its deployment would require extensive discussion with the forecasting agencies, which have complex provincial or national systems to conduct forecasts, as well as with responsible jurisdictions. Second, since an agreement is required, official procedures would need to be deployed in operation and would add delays in the issuing of the forecasts. Finally, as with the option 2, there is no clear indication on how this model would perform better than option 1.

> The current cooperation existing between NOAA and MELCC for issuing forecasts is most agile and does not present any shortcomings that would need to be addressed. There is no technical justification to change the current governance model.probabilistic. Their levels of detail should be coherent with the forecasting skill.

5.3 FLOOD FORECASTING TO SUPPORT FLOW-CONTROL STRUCTURES

Currently there are no operating flow-control structures on Lake Champlain or the Richelieu River. The ILCRRS explored a broad range of structural solutions, including some that involved regulating the full flow regime of the Richelieu River (ILCRR Study Board, 2021c). This type of structure would require flow forecasting for management of the regulation plan. However, those large-scale solutions were rejected by the ILCRR Study Board for a variety of reasons.

Further work considered using the Chambly Canal to route flow during the spring flood. Other efforts focused on selective excavation of the Richelieu River shoal to reduce extreme water levels, such as those that occurred in 2011.

Two promising structural solutions are in the process of being fully assessed by the ILCRR Study Board. They are:

Alternative 1[6]: Selective excavation of the Richelieu River shoal with submerged weir

Alternative 3: Selective excavation of the shoal with submerged weir and a modest Chambly Canal diversion.

Alternative 2, which focused on an optimized diversion scheme (flow of ~400 m^3/s) has been shown to be cost-ineffective. This alternative would have required flood forecasting to support its operational plan.

Alternative 1 does not require flood forecasting for its operation. The modest diversion proposed for Alternative 3 is only ~80 m^3/s and the gates would be targeted to open once a specific water level is reached at the marina in Saint-Jean-sur-Richelieu. This solution might require some level of flood forecasting pending further analysis.

Operation decisions for a modest diversion (Alternative 3) will rely on observed values and not forecasting. Flood forecasting could improve anticipation of these operations; further analysis during the potential deployment of this alternative may be warranted.

[6] Alternative numbering is not sequential as the numbers refer to the complete list of possible mitigation measures as described in the Structural Solutions report (FMMM/HHM 2021).

6 FINDINGS AND RECOMMENDATIONS

Following the topics discussed previously in the report, the main findings are summarized here:

- Production of official flood forecasts for the LCRR system is the responsibility of NOAA (United States) and MELCC (Canada) flood forecasters.
- Both MELCC and NOAA forecasters ensure binational coherence and publish official forecasts limited to their respective area of responsibility.
- The official flood forecasts of NOAA and MELCC are binational because they are produced collaboratively ensuring that no contradictory messages exist.
- Flood forecasting is a federal mandate with NOAA in the United States, which employs a structured and formal national system.
- Flood forecasting is a provincial mandate in Canada. MELCC's forecasting team is completely autonomous with its forecasting processes and collaborates with ECCC, who produces operational hydrological forecasts to support federal mandates other than flood forecasting.
- Models needed to improve flood forecasting were developed during the LCRR study, but not all modelling upgrades have been transitioned to operations yet.
- No major technical barriers exist to implement the recommended FFS. However, transition of new models, products and services to operations can take several years, depending upon forecast system capacity and timelines.
- Agencies responsible for the delivery of flood forecasts have specific technical requirements based on national and provincial systems. These protocols and standards therefore need to be adhered to in the development of the flood forecasting and inundation mapping system for the LCRR basin.
- There is no technical justification to change the current governance model, which has been functioning effectively. No incentives to change were suggested or reported during this study or the more than 10 years of operating with this model.
- Unless and until a modest diversion is deployed, no requirements are specifically linked to a control structure.

Based on these findings and the rest of the report, the following recommendations can be formulated:

1. The flood forecasting system should include a forecasting chain (weather, hydrology, hydrodynamics, data-assimilation and post-processing) producing short term deterministic and long-term ensemble forecasts over the entire LCRR basin by each forecasting agency, or in collaboration. Specific efforts should be deployed to complete the action needed (see Table 1 – FFS Requirements gap analysis).

2. Outputs from various components of the forecasting chain should be made readily available to NOAA's and MELCC's forecasters for integration and binational coherence by their producers (ECCC, NOAA, MELCC).

3. Research and development efforts should be continued on integration of multiple sets of forecast guidance to provide an improved methodology for this specific FFS. In the meantime, MELCC and NOAA forecasters can continue integration using the current hands-on manual approach.

4. The following forecasting products should be made available to the users: (1) short term inundation maps including uncertainty (i.e., probability associated scenarios) for at least a two-day horizon (and up to five days if skill is sufficient) and (2) long-term probabilistic forecasts as graphs.

5. A combination of simple and more complex hydraulic and hydrodynamic models can be used. For short term forecasts out to five days, wind and wave effects on Lake Champlain water levels must be included in lake level predictions. For longer term forecasts, wind and wave effects can be included pending proper skill assessments.

6. NOAA and MELCC forecasters must continue to ensure binational coherence between their respective official forecasts.

7. If Alternative 3 of the structural mitigation measures is deployed (selective excavation of the shoal with installation of submerged weir and a modest Chambly Canal diversion), the FFS will need to include the management rules for the weir and diversion, and their effect on the system's water balance. Forecasts will also need to be provided to the manager of the structures with an accuracy and lead time that supports decisions needed for flood management.

8. NOAA and MELCC must maintain their collaboration on forecasts within the current governance model. ECCC must also make readily available to both NOAA and MELCC the operational runs of the forecasting chain components they are running (ex: NSRPS, H2D2). Improvements to national-level models and sources of forecast guidance that can be joined to produce binational probabilistic stream predictions should be coordinated through the NOAA-ECCC bilateral agreement while making sure the MELCC's official forecast producer is respected.

REFERENCES

Carrera, M.L., S. Bélair, and B. Bilodeau, 2015. The Canadian Land Data Assimilation System (CaLDAS): Description and Synthetic Evaluation Study, Journal of Hydrometeorology, 16-3.

Clemen, R.T., 1989. Combining forecasts: A review and annotated bibliography. International Journal of Forecasting, 5(4), pp. 559-583.

Flood Management and Mitigation Measures Technical Working Group and Hydrology, Hydraulics, and Mapping Technical Working Group (FMMM/HHM), 2021. Potential Structural Solutions to Mitigate Flooding in the Lake Champlain-Richelieu River Basin. International Lake Champlain – Richelieu River Study. A report to the International Joint Commission. https://ijc.org/en/lcrr/potential-structural-solutions-mitigate-flooding-lake-champlain-richelieu-river-basin

Fortin, V., G. Roy, T. Stadnyk, K. Koenig, N. Gasset & A. Mahidjiba, 2018. Ten Years of Science Based on the Canadian Precipitation Analysis: A CaPA System Overview and Literature Review, Atmosphere-Ocean, 56:3, 178-196, DOI: 10.1080/07055900.2018.1474728

Gaborit, E., Fortin, V.,Xu, X. Y., Seglenieks, F., Tolson, B., Fry, L. M., Hunter, T., Anctil, F., Gronewold, A. D., 2017. A hydrological prediction system based on the SVS land-surface scheme: efficient calibration of GEM-Hydro for streamflow simulation over the Lake Ontario basin, Hydrol. Earth Syst. Sci., 21, 4825–4839

Hawcroft, M., Lavender, S., Copsey, D., Milton, S., Rodríguez, J., Tennant, W., Webster, S. and Cowan, T., 2021. The benefits of ensemble prediction for forecasting an extreme event: The Queensland Floods of February 2019. Monthly Weather Review.

International Joint Commission, 2015. Progress towards an operational real-time flood forecasting and flood inundation mapping system for the Lake Champlain and Richelieu River.

International Lake Champlain-Richelieu River Study Board, 2021a. Proceedings of the ILCRR Study -Québec Workshops on Municipal Needs Assessment on Flood Forecasting and Emergency Measures.

International Lake Champlain-Richelieu River Study Board, 2021b. US SPE Theme 3 Report.

Lachance-Cloutier, S., Turcotte, R., Cyr, J. F., 2017. Combining streamflow observations and hydrologic simulations for the retrospective estimation of daily streamflow for ungauged rivers in southern Québec (Canada). Journal of Hydrology, 550, 294–306.

Seiller G, Anctil F, Roy R., 2017. Design and experimentation of an empirical multistructure framework for accurate, sharp and reliable hydrological ensembles. Journal of Hydrology 552, 313-340.

Zhu, Yuejian, 2005. Ensemble forecast: A new approach to uncertainty and predictability. Advances in Atmospheric Sciences 22, 781-788.

APPENDIX A - Flood emergency responders' needs assessment

CONTEXT

Emergency responders were solicited on both sides of the border as to their needs for products and services required from the flood forecasting and inundation mapping system. Engaging emergency responders during the Covid-19 pandemic presented particular challenges. As can be expected, the needs that were expressed are different on the US side than on the Canadian side. The US side of the LCRR is comprised of Lake Champlain, a lacustrine environment, whereas a riverine environment, the Richelieu River, comprises most of the Canadian side (except for Missisquoi Bay). This hydraulic setting makes the response time for rising flood levels slower in the United States than in Canada. Flood-proofing activities also have taken place on both sides of the border, with flooding along the lake shore becoming less of an issue with time. These factors impacted the level of interest and feedback received regarding emergency responders' needs. Engagement of emergency responders in Canada and the United States is described below.

QUÉBEC

In Québec, a series of workshops was conducted to assess emergency responders' needs. A total of 10 communities located along the Richelieu River participated in the workshops. Seven of them were fully engaged and completed the survey on their flood preparation activities and their informational needs. Details on the workshops and responses received are captured in the report entitled, "Proceedings of the ILCRR Study -Québec Workshops on Municipal Needs Assessment on Flood Forecasting and Emergency Measures" (2021a).

The workshops focused on addressing two specific questions:

1. Does having a five-day flow forecast help you to be better prepared for a flood?
2. Do the Study tools and products help improve your flood emergency response and preparedness?

In early discussions at a meeting (June 2020) with emergency responders, they expressed general satisfaction with existing forecasting products and stated that a longer, five-day forecast probably would be more useful, depending on its accuracy. here was no clear response regarding the utility of various mapping products that were presented.

After participating in a "virtual flood" exercise in the workshops, the responders had a stronger positive opinion of the utility of a five-day forecast and the various mapping products. Figure A-1 illustrates the virtual flood that was presented. The exercise allowed the emergency responders to more clearly determine the benefits of having a 5-day forecast and how it could impact their flood response actions. Risk tolerance is an important consideration that varies from community to community. The emergency responders found that the percentile bands (10%, 50%, 90%) were useful for framing uncertainty. Depending on their circumstances and past experiences in dealing with floods, they found this information to be particularly helpful for decision-making. Interestingly, those communities that thought they addressed the 2011 flood relatively well erred on the more optimistic side, while those that did not consider that they did well focused on the pessimistic estimate. Of course, other factors come into play in their decision making, such as the time required to prepare for the flood and the potential consequences.

The emergency responders expressed interest in a longer-term forecast (3 weeks to 1 month) to provide them more lead time for a pending flood. They recognize that there is greater uncertainty associated with a longer-term forecast. However, this additional lead time would help them in contracting materials and equipment needed to address the flood. Smaller communities also work collaboratively, so this helps from a planning perspective, where sharing is involved.

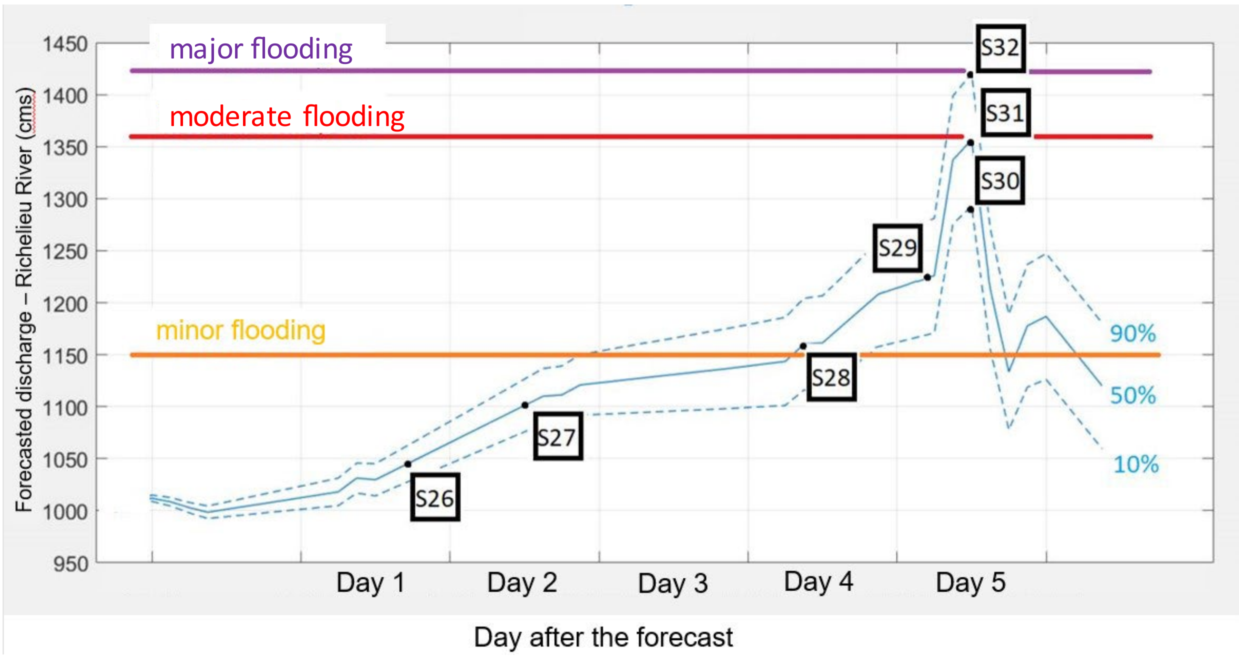


Figure A-1 Virtual flood exercise conducted with emergency responders in Québec (S values pointed the user to the right map number during the exercise.)

The emergency responders were presented with a variety of mapping products that show the impacts for each of the scenarios (e.g., S26) specifically for their community. These products included: the areal extent of flooding (inundation map), road accessibility and social vulnerability. This information is not shown here for confidentially reasons, because of the granularity (i.e. detail) of the sensitive information that is displayed.

The emergency responders helped in validating the mapping products based on their knowledge. They noted that some roads had been raised since 2011 and therefore the maps need to be updated. Also, many residences have been flood-proofed and this needs to be accounted for. In general, they thought the inundation maps reflected reality based on their knowledge of past flooding. They found this product to be particularly useful.

The emergency responders agreed that these visual outputs provided them with more detailed information to make better informed decisions. They all expressed an interest in seeing this information being made available to address future floods.

New York and Vermont

On the US side, it was a challenge engaging emergency responders in a more formal exercise for the reasons stated earlier (less interest due to less direct impact from recent floods, and the Covid-19 pandemic). Instead, five individuals from key state agencies were interviewed to get their feedback. Details on the questions and responses for the interviews are captured in, "US SPE Theme 3 Report" (ILCRRSB 2021b).

In general. the agency personnel are satisfied with the flood forecasting products being produced, but expressed an interest in the improved wave forecasts that are currently being worked on. They also thought a more coordinated approach, with more integrated planning at the state-level, would help improve flood emergency response.

Lake shore flooding was an issue for both states. However, tributary flooding was identified to be a more significant concern. Flood forecasting products therefore need to focus on this scale of flooding and provide higher resolution outputs.

APPENDIX B - ECCC weather forecast model configuration and skill metrics

The High-Resolution Deterministic Prediction System (HRDPS) and the actual configuration of the Global Ensemble/Deterministic Prediction System (GDPS/GEPS) and Regional Deterministic/Ensemble Prediction System (RDPS/REPS) constitute a cascade of nested LAM (Limited Area Model) versions of the GEM atmospheric models with increasing resolution. They produce deterministic and ensemble predictions over most of Canada up to four times each day. Each system is configured as follows: The Global Deterministic Prediction System (GDPS) relies on a configuration of GEM having a resolution of 15 km and a forecast horizon of 10 days. Forecasts are issued at 00 and 12 UTC on a grid covering the entire globe. The GDPS is two-way coupled to the Nucleus for European Modelling of the Ocean (NEMO) model.

The Global Ensemble Prediction System (GEPS) is an ensemble version of the GDPS that relies on a GEM configuration at 40-km. Forecasts are issued at 00 and 12 UTC on a global grid. The forecast horizon is 16 days, extended to 32 days for the forecast issued each Thursday at 00 UTC. Outputs are available every 3h for lead times covering the first week, and every 6h for longer lead times. The GEPS is two-way coupled to the NEMO model. As an ensemble prediction system, the GEPS runs twenty forecast scenarios (or ensemble members) aiming at representing the forecast uncertainty. The system is part of a multi-model ensemble forecasting system named the North American Ensemble Forecasting System (NAEFS), currently composed of 20 members from the GEPS and 20 members from the US National Centers for Environmental Prediction (NCEP) Global Ensemble Forecasting System (GEFS). NAEFS has been shown to outperform both GEPS and GEFS individually.

The Regional Deterministic Prediction System (RDPS) relies on a configuration of GEM having a resolution of 10 km and a forecast horizon of three days. Forecasts are issued four times per day (at 00, 06, 12 and 18 UTC) on a grid covering most of North America.

The ensemble version of the RDPS is the Regional Ensemble Prediction System (REPS), which relies on a configuration of GEM having a resolution of 10 km and a forecast horizon of three days. Forecasts are issued at 00 and 12 UTC on a grid covering North America. As for the GEPS, the REPS runs 20 forecast scenarios (members) to reproduce forecast uncertainty. The High-Resolution Deterministic Prediction System (HRDPS) relies on a configuration of GEM having a resolution of 2.5 km and a forecast horizon of two days. Forecasts are issued four times per day (at 00, 06, 12 and 18 UTC) on a grid covering continental Canada as well as all transboundary watersheds.

Although these forecasting systems do not include river routing, they all forecast surface processes, including surface runoff. Furthermore, the GEPS ensemble surface runoffs are post-processed to compute the surface runoff climatological anomaly (forecasted runoff minus its model climatology). These series can be used to identify areas at risk of flooding. For example, Figure B-1 shows the Extreme Surface Runoff Outlook issued on April 11, 2019, and valid for the week of April 18-25. Areas with an above-average risk of extreme surface runoff are shown in yellow, and areas with an extreme risk are shown in red. In this forecast product, a broad area of above-average risk of extreme surface runoff, encompassing the LCRR, is visible. Flooding did occur during that week on the watershed of the LCRR.

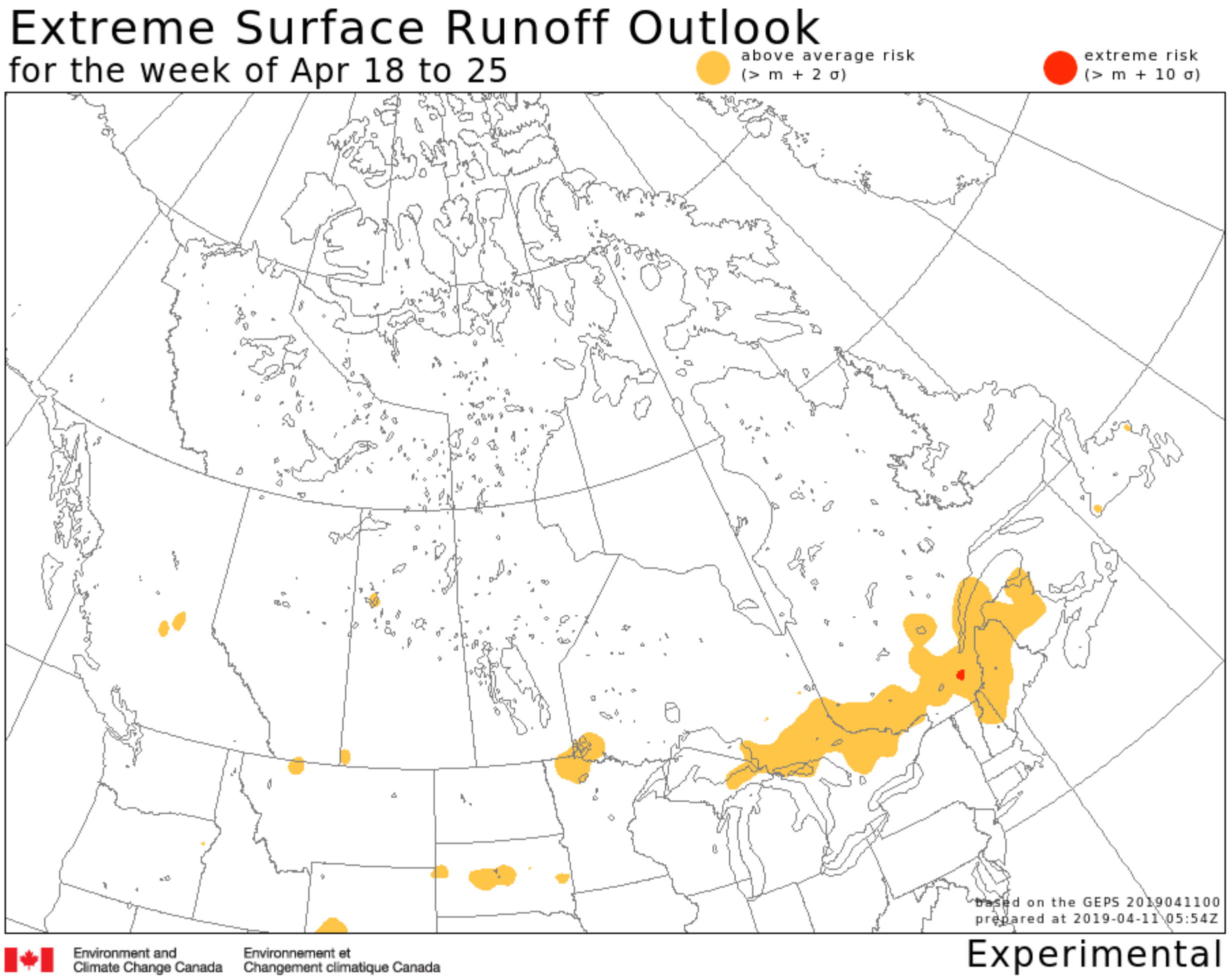


Figure B-1. Extreme Surface Runoff Outlook issued on April 11 for the week of April 18-25, 2019.

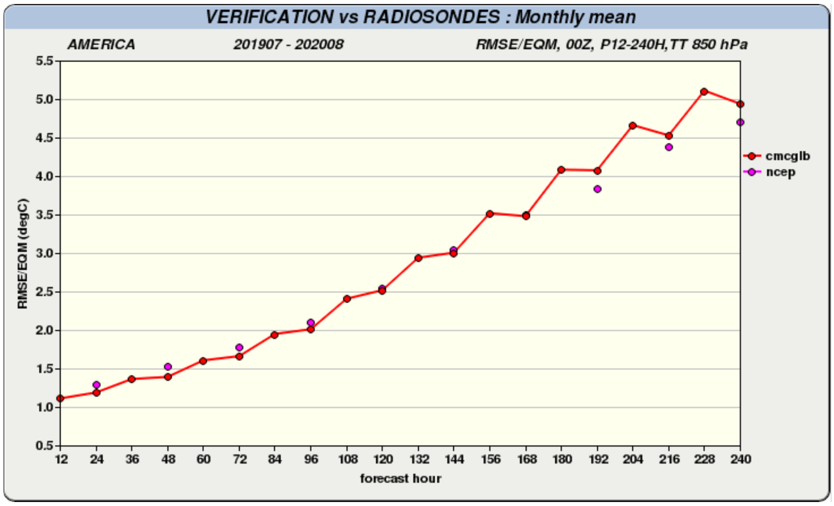
Finally, the Water Cycle Prediction System (WCPS; Durnford et al., 2018[7]) is a chain of interconnected models that represents the full water cycle from the atmosphere to the surface, through rivers and lakes, and back to the atmosphere. It includes atmospheric, ocean, lake, marine ice and river routing schemes operational over the Laurentian Great Lakes. Specifically, the WCPS relies on a configuration of GEM having a resolution of 10 km and a forecast horizon of three days. Forecasts are issued twice daily (at 00 and 12 UTC) on a grid covering the watershed of the St. Lawrence River at Tadoussac (therefore including Lake Champlain). In the experimental version presently run at ECCC, this system is two-way coupled with NEMO over the Great Lakes, and the 1-km resolution WATROUTE river model over all tributaries of the St. Lawrence River. It thus simulates the current and future states of the land, lakes and rivers, but it does not represent operationally the impact of wind on the lake level or on the flow of the Richelieu River. System configurations presently used at ECCC are summarized in Table B-1. However, note that these details are likely to change in the future, following the improvement of each system. The official documentation, including a detailed change log is maintained on the GitHub platform (https://eccc-msc.github.io/open-data/msc-data/readme_en/).

[7] https://doi.org/10.1175/BAMS-D-16-0155.1

Table B-1. Configuration of operational weather, surface and river prediction systems based on the GEM model over the LCRR.

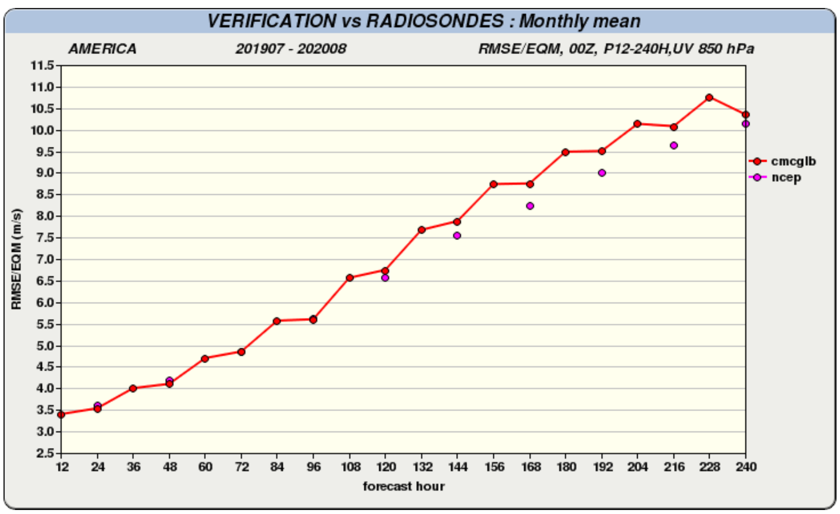
System	Resolution	Forecast horizon	Forecasts per day	Ensemble forecasts	Runoff forecasts	River forecasts
GEPS	40 km	16 days (32 days each Thursday)	2	Yes, 20 members	Yes, 20 members	No
GDPS	15 km	10 days	2	No	Yes	No
REPS	10 km	3 days	2	Yes, 20 members	Yes, 20 members	No
RDPS	10 km	3 days	4	No	Yes	No
HRDPS	2.5 km	48 hours	4	No	Yes	No
WCPS	10 km	3 days	2	No	Yes	Yes, at 1 km

Forecasts are compared to observations and to forecasts from other national forecasting centers on a routine basis. For example, Figure B-2 shows the growth of temperature forecast errors as a function of lead time over North America. Forecasts are compared to radiosonde observations at 850 hPa (which is about 1500 m above the surface) for the Canadian Global Deterministic Prediction System (GDPS, in red) and the US Global Forecasting System (GFS, in magenta). The evaluation period is from July 2019 through August 2020, as a major upgrade to the GDPS occurred on July 3, 2019. The Root Mean Square Error (RMSE) of GDPS and GFS forecasts are comparable, the GDPS being slightly better for days 1-4 and the GFS being slightly better for days 7-10 for this specific period (July 2019 – August 2020). Figure B-3 presents a comparison of the same two models using the same dataset and error metric, but for wind speed. Again, the RMSE of GDPS and GFS forecasts are comparable, with the GFS being slightly better for days 5-10 of this period. Over the last few years, verification scores for GDPS and GFS have been very similar, and scores have been steadily improving.



Red: Canadian Global Deterministic Prediction System (GDPS), Magenta: US Global Forecasting System (GFS)

Figure B-2. Root Mean Square Error (RMSE) of temperature forecasts at 850 hPa for the period of October 2018 – September 2019 over North America, expressed as a function of lead time.



Red: Canadian Global Deterministic Prediction System (GDPS), Magenta: US Global Forecasting System (GFS)

Figure B-3. Root Mean Square Error (RMSE) of wind speed forecasts at 850 hPa for the period of October 2018 – September 2019 over North America, expressed as a function of lead time.

The quasi-linear growth of error for temperature and wind speed over a ten-day period must be kept in mind when designing a water level forecasting system for the LCRR, given the influence of temperature (especially through snowmelt) and wind on lake levels. Another important variable controlling lake level changes is obviously precipitation. Figure B-4 shows the evolution of the Equitable Threat Score (ETS) as a function of lead time for GDPS forecasts (in blue) and RDPS forecasts (in red) of precipitation events of more than 5mm / 6h during the spring of 2019 (March-April-May). ETS is a positively oriented measure of forecast skill frequently used for precipitation forecasts. A perfect forecast has an ETS value of one, and negative values of ETS indicate forecasts that have no skill. It can be seen that 10-day GDPS forecasts of precipitation have very little skill. In fact, there is a limited skill after even five days in this deterministic forecast. It can also be observed that GDPS and RDPS forecasts have essentially the same skill over the first three days, even if RDPS forecasts have a better horizontal resolution.

Instead of increasing the horizontal resolution of a deterministic forecast, it is often more beneficial to produce an ensemble forecast. This is both a way of representing dynamically the uncertainty in the forecast and increasing the skill of the forecast. Multi-model ensemble weather forecasting systems such as the NAEFS (a coordinated Canada-US-Mexico ensemble weather forecasting system) are recommended in order to maximize skill. Figure B-5 presents the Brier Skill Score (BSS) for NAEFS precipitation forecasts of more than 15 mm in 24 hr, assessed over the whole globe for the period of April 2019 – June 2019. The BSS is a positively oriented skill score frequently used for probabilistic forecasts of precipitation. A value of one indicates a perfect forecast, and a value of zero indicates a forecast that has no more skill than climatology. Although NAEFS forecasts have been shown to outperform deterministic forecasts for most variables at long lead times, it can be seen that the skill of precipitation forecasts for the second week of a forecast is significantly less than for the first week. In practice, NAEFS forecasts for 15 mm of precipitation in 24 hr have very little skill for lead times of more than 10 days.

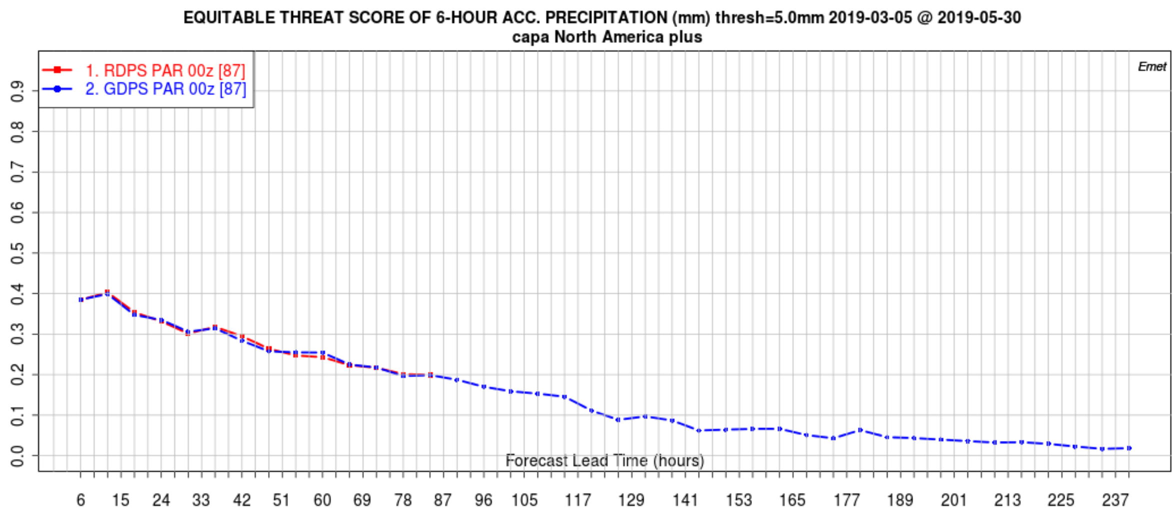
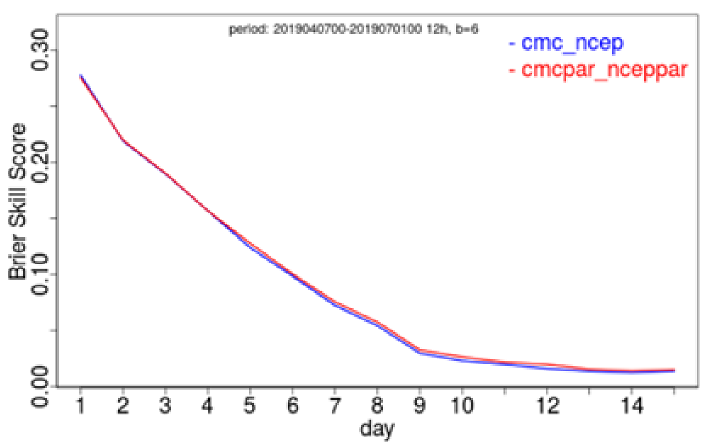


Figure B-4. Equitable Threat Score (ETS) of precipitation forecasts for the period of March 2019 – May 2019 over North America, expressed as a function of lead time. Red: Canadian Regional Deterministic Prediction System (RDPS), Blue: Canadian Global Deterministic.



Red: skills of NAEFS forecasting system implemented in July 2019, Blue: skills of previous NAEFS

Figure B-5. Brier Skill Score (BSS) of 15mm/24h precipitation forecasts for the period of April 2019 - June 2019 over the globe, expressed as a function of lead time.

APPENDIX C - NOAA weather forecast model configuration

NOAA's Weather Prediction Center (WPC) issues forecasts for North America four times daily. These forecasts are informed by multiple atmospheric models, including the Global Forecast System (GFS), the North American Mesoscale (NAM) forecast system, the European Centre for Medium-Range Weather Forecasts (ECMWF) global model, the High-Resolution Rapid Refresh (HRRR) model, and the National Blend of Models (NBM), among others. Each of the atmospheric models that WPC considers when developing their forecast is available at different spatial resolutions and time horizons.

WPC - WPC model forecasts are generally issued via raster format for 168-hour periods at various resolutions, including a 2.5 km grid scale, which is ingested into NERFC's configuration of the NWS Advanced Weather Interactive Processing System (AWIPS). While the grids of each WPC forecast are ingested into AWIPS as they become available, so are each of the individual models that WPC considers in developing their forecast. With all of these different model grids available to NWS weather and water forecasters, the locally generated Quantitative Precipitation Forecasts (QPF) that are used for hydrologic model forcing can be based on any of these models. That is, hydrologic forecasters at the NERFC can choose which atmospheric model(s) can be leveraged in developing the local hydrologic forecasts.

GFS – The Global Forecast System model is produced by the NWS National Centers for Environmental Prediction (NCEP) four times daily at iterations for the 00z, 06z, 12z, and 18z cycles. The model covers the entire globe and its time horizon is 192 hours. Horizontal resolution of the model varies with approximately 28 km between grid points for the first week of the forecast and 70 km between grid points for the balance of the forecast.

NAM – The North American Mesoscale Forecast System model is also produced by NCEP four times daily at iterations for the 00z, 06z, 12z, and 18z cycles. The model's spatial domain is the North American continent. Horizontal resolution and time horizon of the NAM varies. The finer scale version of the NAM has a 12 km resolution and provides the forecast out to 84 hours. There are 20 km and 40 km resolution versions of the model that extend the forecast to just 60 hours.

ECMWF – The European Centre for Medium-Range Weather Forecasts model is issued by the Copernicus Atmosphere Modelling Service in Reading, United Kingdom twice daily for the 00z and 12z cycles at various spatial scales and resolutions. The high resolution (HRES) medium-range global forecast is one of 52 members in the ECMWF ensemble and is produced at a 9 km resolution for a time horizon of 10 days. Grids for this version of the model are ingested into AWIPS for analysis and comparison by NWS forecasters.

HRRR – The operational version of the High-Resolution Rapid Refresh model (version 4) is produced by NCEP each hour at a fine-scale 3 km horizontal resolution. The time horizon for each model run is just 18 hours, but is extended to 48 hours for each iteration of the 00z, 06z, 12z, and 18z cycles. Two spatial domains of the operational HRRR are currently produced, one for the conterminous United States and one for the Alaskan region.

NBM – The National Blend of Models is issued twice daily via the NCEP Weather Prediction Center (WPC) for the 00z and 12z cycles. The time horizon of the model grids that are ingested into AWIPS is 11 days (264 hours). Multiple grid resolutions and spatial domains are produced, with the CONUS and Hawaii domains based on a 2.5 km grid and the Alaska domain based on a 3 km grid. Open ocean domain products are also available at a resolution of 10 km.

GEFS – The Global Ensemble Forecast System weather forecast model is issued by NCEP four times daily for the 00z, 06z, 12z, and 18z cycles. Version 12.0 of the GEFS was implemented in 2020 and includes 31 individual forecast members. Each member represents a small perturbation to the weather observations used to initialize the baseline GFS forecast. Altogether, the 31 members help to provide an estimate of forecast uncertainty. The time horizon for the GEFS is generally set at 16 days, although the daily 00z run extends out to 35 days. Horizontal resolution of the GEFS was increased to ~25 km for version 12.0.

NAEFS – The North American Ensemble Forecast System is a joint project involving the weather agencies of Canada, Mexico, and the United States. The NAEFS produces forecast guidance based on 21-member ensemble forecasts from both NCEP and ECCC. The model is run twice daily for the 00z and 12z cycles. Grids are distributed on a 1x1 degree resolution and extend out to 14 days.

APPENDIX D - NSRPS model technical details

Figure D-1 schematically represents the NSRPS structure and the correspondence between the deterministic and ensemble components of the system. In this figure, the connections with the H2D2 model are depicted as dotted lines since the system is currently under development (the deterministic version is expected to be completed within a year).

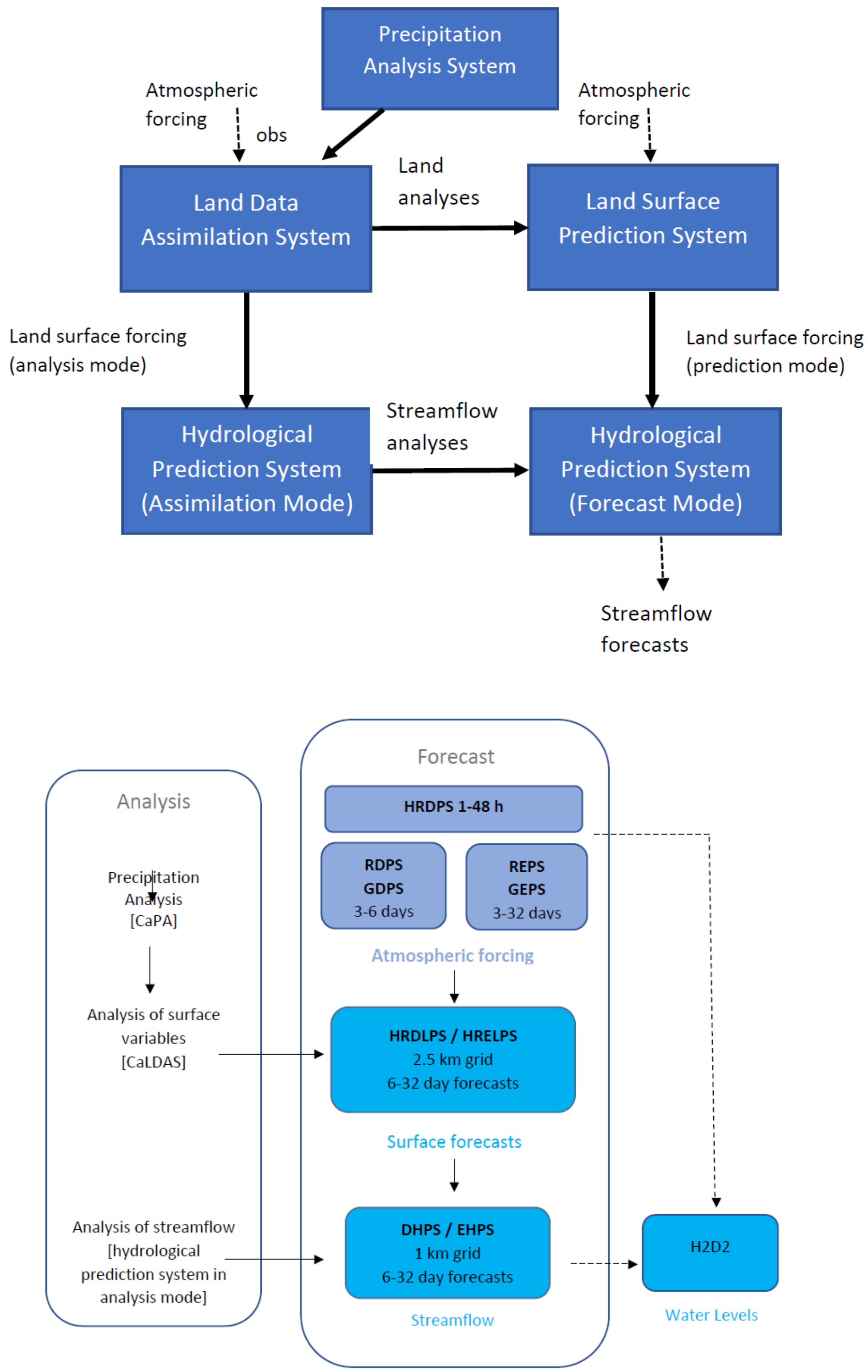


Figure D-1. Schematic of the National Surface and River Prediction System (NSRPS) in its deterministic (operational) and ensemble (experimental) versions. The ensemble hydrodynamic forecast component (dotted lines) is in development.

Figure D-2 shows a six-day streamflow deterministic forecast issued by the NSRPS on October 1, 2019 at 00 UTC, forecasting flows for October 7, 2019 at 00 UTC, centered on the LCRR watershed. Colors reflect the streamflow forecast, in cubic meters per second, of each 1 km^2 grid cell. The forecasted time series can be obtained for any grid cell (e.g., Fig D-3) or represented as a forecasted hydrograph for a specific lead time for any gauged location in the watershed (e.g., Fig D-4). Figure D-3 shows examples of two different levels of model skill within the existing system.

Although the WCPS and the NSRPS are fully automated systems, they are continuously monitored to ensure that quality inputs are provided to the system and that the models and data assimilation systems perform as expected. Equally important, ongoing research aims at assessing the nature and magnitude of hydrological forecast errors (e.g., accuracy, bias, and reliability of ensemble forecasts) as well as characterizing the uncertainty of the hydrodynamic system incomes (precipitation, streamflow, wind).

At present, no flood mapping and flood alert system is in operation for the LCRR at ECCC. However, an ongoing collaboration with the MELCC aims at developing forecasts that combine numerical predictions from various sources (e.g., various modelling systems and organizations). This is expected to improve the hydrological and hydrodynamic forecasts and provide tools to produce complete flood risk information.

The NSRPS has been shown to provide better streamflow forecasts than the WCPS in summer and fall. Comparable skill is currently expected in winter and for the spring freshet. Other advantages of the NSRPS include the higher resolution of the atmospheric forcing for the first two days (2.5 km versus 10 km) and the longer lead time of the forecast (six days versus three days for the deterministic forecast, 16 days for the ensemble forecast, and 32 days for the ensemble forecast issued on Thursdays).

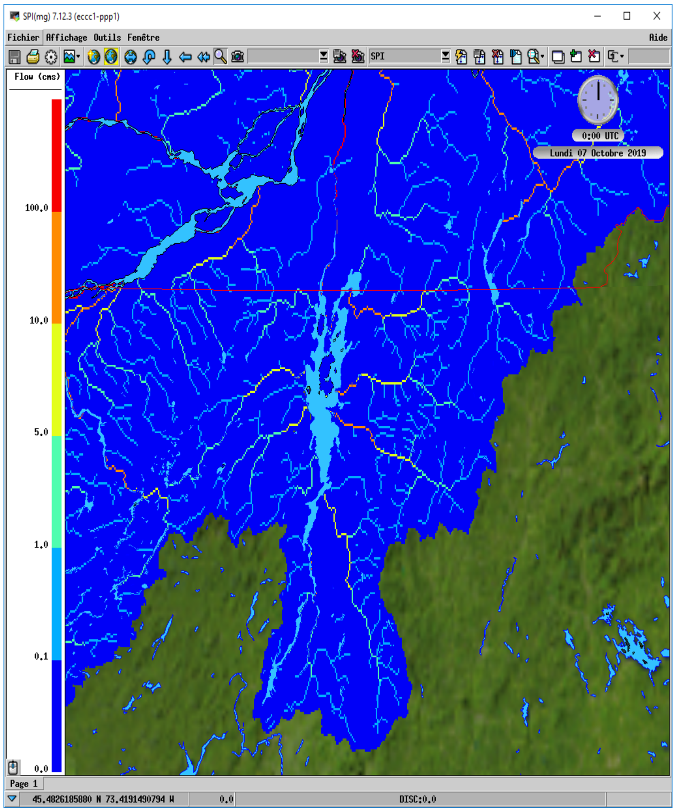


Figure D-2. NSRPS Streamflow forecast issued at 00 UTC on October 1, 2019 forecasting flows for October 7, 2019 at 00 UTC.

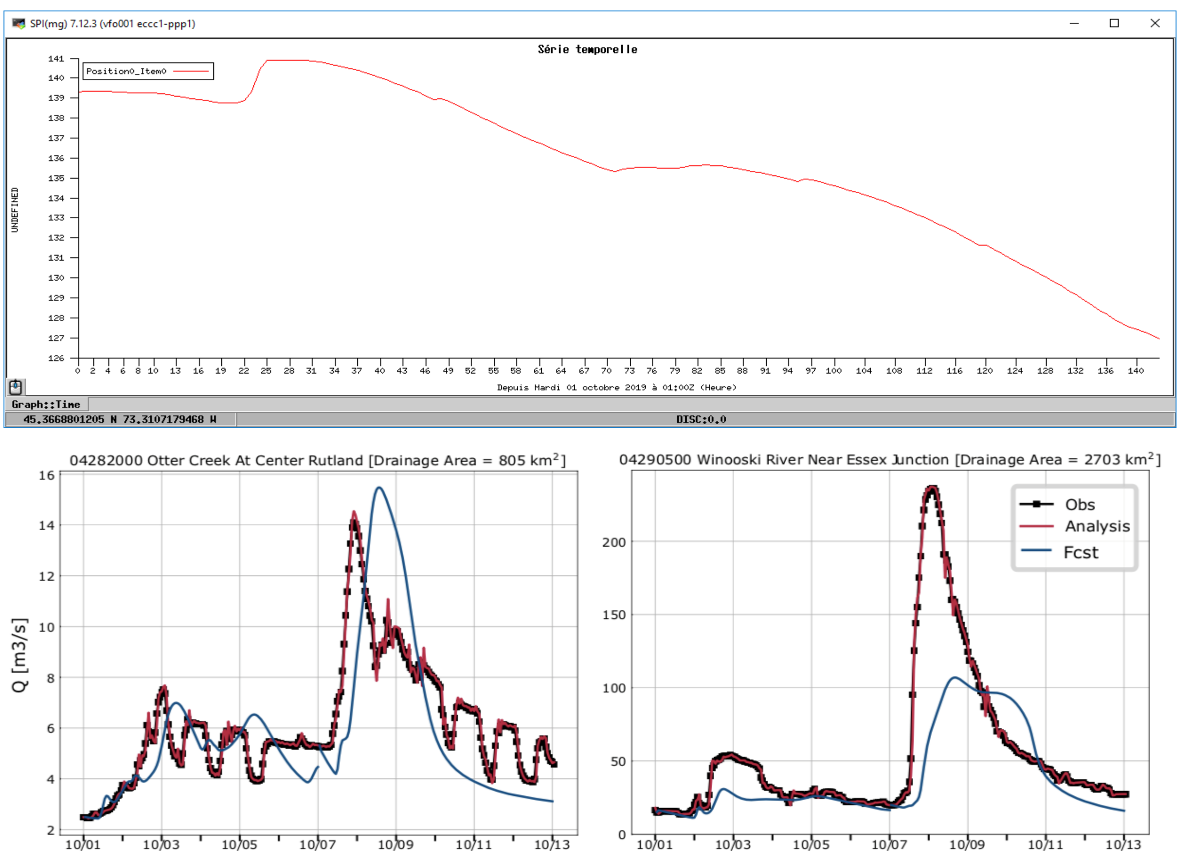


Figure D-3. Example of NSRPS Streamflow forecast issued at 00 UTC on October 1 and 7, 2019 for two tributaries of the LCRR.

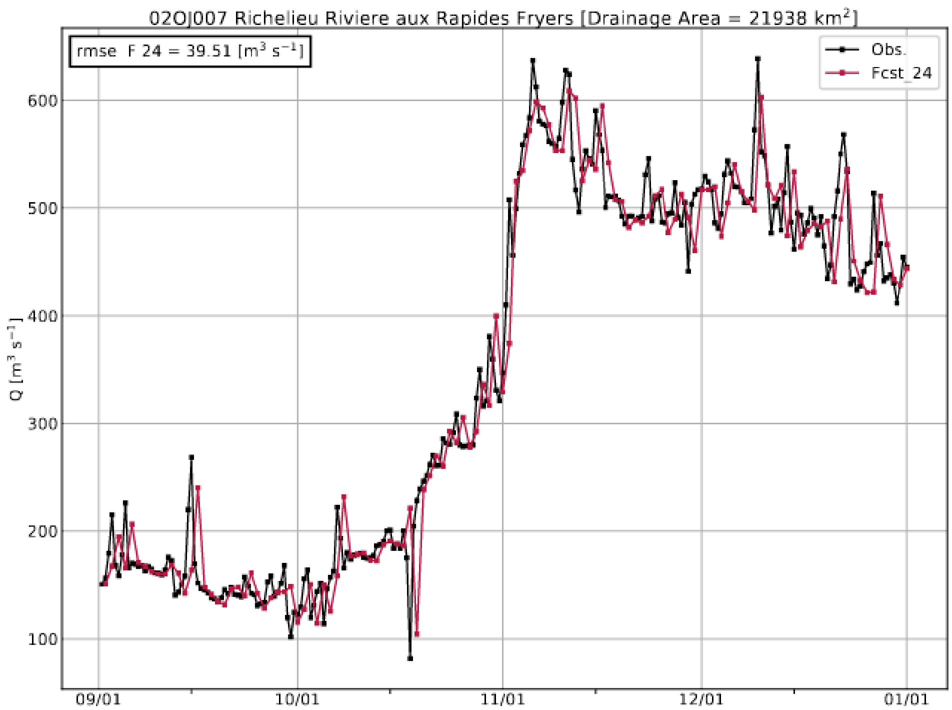


Figure D-4. Example of NSRPS Streamflow forecast at 24h at Saint-Jean-sur-Richelieu over Fall 2019.

APPENDIX E - Detailed equations and operation of the water balance model

This equation reflects the balance between the change in lake volume, the outflow from the Richelieu River, and the Net Basin Supplies (NBS) from Lee (1992) and Bruxer (2011):

$$\Delta S \pm \Delta Sth = P + R \pm G - E - O - C \qquad (1)$$

Where:

ΔS = change in lake volume

ΔSth = thermal expansion and contraction, which can be neglected

P = precipitation on the lake

R = runoff and contributions from tributaries to the lake

G = groundwater flow

E = lake evaporation

O = outflow to the Richelieu River

C = water withdrawal

NBS can be defined in terms of its components:

$$NBS = P + R \pm G - E \qquad (2)$$

Because records of these components are incomplete or not measured, NBS can more usefully be defined as the inflow (less evaporation) volume, which must equal the change in the lake volume plus the volume of water that flows out of the lake:

$$NBS = \Delta S + O \qquad (3)$$

The WBM noted in equation (3) is first used in establishing the historical NBS series at a quarter-month (QM) time step. In other words, the NBS corresponds to the sum of the variation in lake level as translated into flow (positive for an increase in water level and negative for a decrease) and the average outflow into the Richelieu River, on a QM basis. This established the historical NBS that is considered a certified series for the basis of comparison for any other data generated by stochastic analysis or from climate forcing.

In the second stage, the same equation is used in evaluating the impact of structural alternatives by adjusting the stage-discharge function based on the results of multiple simulations with the H2D2 two-dimensional hydraulic model (described in Section 4.2).

Water level fluctuations in Lake Champlain are slow due to the large storage capacity of this water body. The quarter-month time step is therefore considered adequate to quantify the effect on lake levels of the different outflow situations. An iterative process is used to solve the mass conservation equation.

The Manning-Strickler formula is used to define discharge in terms of channel geometry, roughness parameters, bed/water surface slope, etc. Using known discharge and a measured cross-section at the Saint-Jean-sur-Richelieu virtual station, the variation of Manning's n is computed for the most recent period, 2010 to 2016. This varied from a low of 0.071 in QM 14 to a high of 0.14 in QM 33.

To operate the water balance model, an initial state of the system is first established with a level of Lake Champlain and a flow from the Richelieu River representing the situation at the beginning of the first QM. Then the steps are the following:

> **Step 1**: A level of Lake Champlain (end of QM) is calculated based on the average of the flows of the Richelieu River at the end and beginning of QM, as well as the NBS for the QM considered. During the very first iteration of a given QM, the flows of the Richelieu River at the end and beginning of the QM are identical.
>
> **Step 2**: A level from the Richelieu to the virtual station at Saint-Jean-sur-Richelieu (end of QM) is calculated using the Manning-Strickler formula based on the lake level (end of QM) and the flow of the Richelieu River (end of QM).
>
> **Step 3**: The stage-discharge is computed with 2D hydraulic model simulations. The water level at the virtual station is calculated with it (Step 4). The Manning-Strickler equation is used to "transfer" the water level of the virtual station to the Lake during the iterative process at Step 2. The final WL of the QM is calculated at Step 4.
>
> **Step 4**: A new flow of the Richelieu River (end of QM) is calculated using the level-flow relationship at the Saint-Jean-sur-Richelieu virtual station. There is iteration for Steps 2 to 4 to obtain a convergence on the level and flow at Saint-Jean-sur-Richelieu. The next action is a return to Step 1.

The iterative process (Steps 1 to 4) continues until Lake Champlain level convergence is achieved (end of QM). The process is repeated for the next QM, until the series is fully processed.

All these variables are interdependent of each other. Therefore, these iterative processes are necessary to achieve a balance every quarter-month. For its part, the historical NBS series is fixed.

APPENDIX F - Forecasting services and skill metrics for Canada

Within Canada, MELCC focuses on producing the forecast for the tributaries to the St. Lawrence River. The flood forecasts for the St. Lawrence River itself are produced at the federal level by Fisheries and Ocean Canada and provided to the MSP.

The MELCC's forecasting team produces water forecasts (flow and/or stage) for over 130 locations across the province of Québec (Figure F-1), including the Canadian part of the Richelieu River and its main tributaries (L'Acadie River and Des Hurons River).

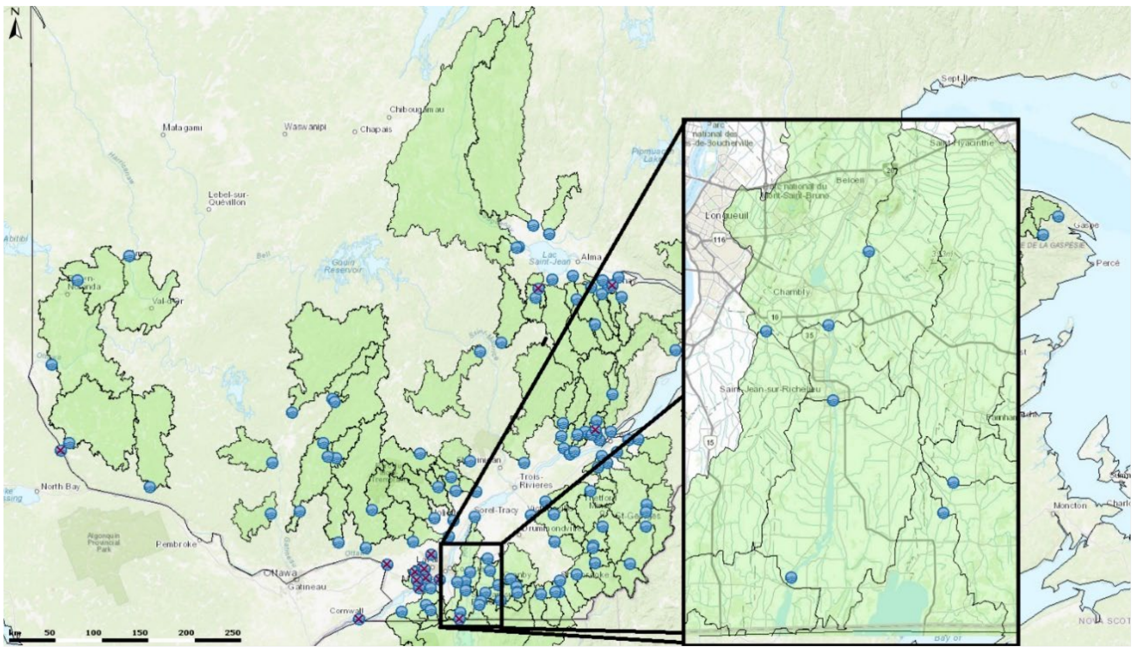


Figure F-1. MELCC forecasting locations on the LCRR basin.

MELCC uses the Deltares' Delft-FEWS (Flood Early Warning System) software combined with the semi-distributed hydrological model, Hydrotel, from Institut Nationale de la Recherche Scientifique – Eau, Terre et Environnement (INRS-ETE) to produce three-to-five-day forecasts into the future. Forecasters use a hands-on approach for data assimilation to adjust model states with current observed condition. This can translate in manually correcting the discharge of Lake Champlain in the forecast to account for wind effects or shift in the stage-discharge curve caused by ice or aquatic plants.

Forecasts specific to the Richelieu River include the forcing provided by NERFC's stage forecast at Rouses Point. Inflows from the Canadian part of the catchment are added and routed using Hydrotel. Stage data measured at Saint-Jean-sur-Richelieu and Saint-Paul-de-l'Île-aux-Noix, as well as discharge data measured at Carignan, are used for data assimilation. Stage-discharge relations are used at various locations. Figure F-2 shows the discharge and stage forecasts at upper river locations (between the international border and the Chambly basin).

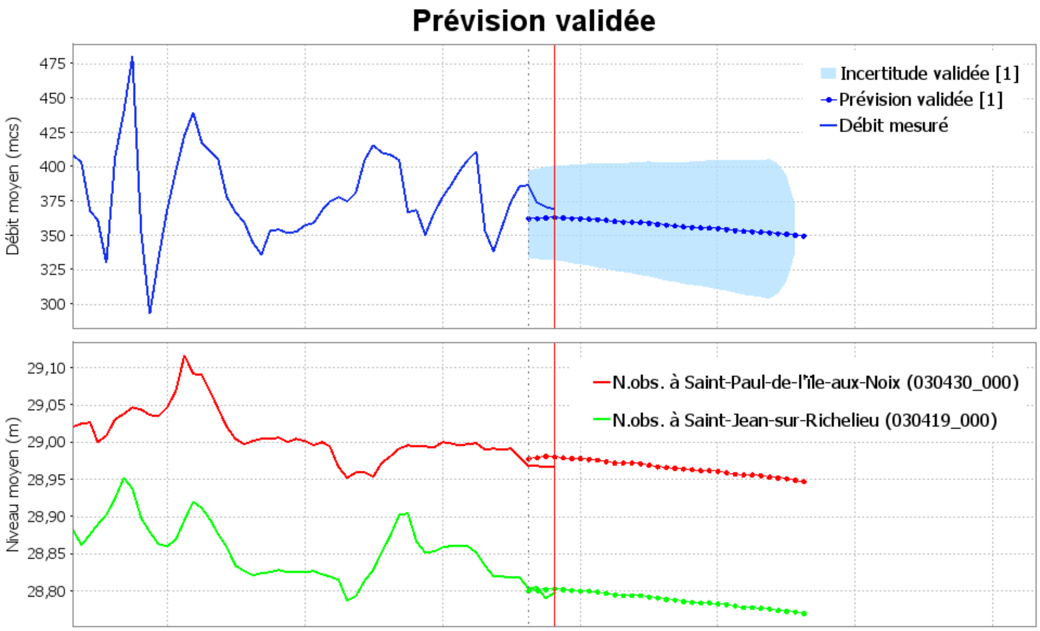


Figure F-2.-MELCC discharge and stage forecasts at upper Richelieu River locations (French only).

The forecasts are typically produced before 10 AM using the previous day's NERFC forecasts as the upstream boundary condition at Rouses Point. Updates are made as required throughout the day as new observations and forecasts become available. Forecast data are made available on the MELCC's website as well as the MSP's Vigilance Crue platform that provides public web access as well as restricted access for emergency managers that contains more information (see Figure F-3 - MSP Vigilance platform accessible by the public).

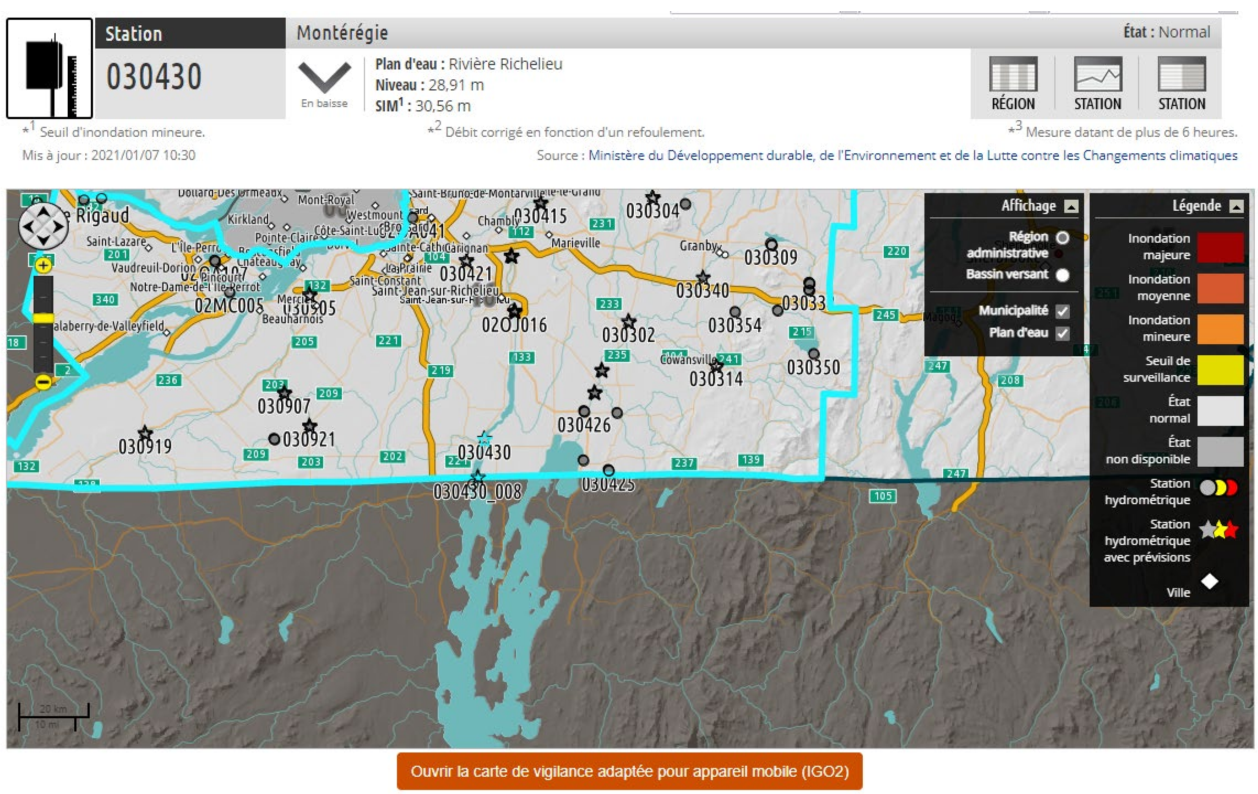


Figure F-3. MSP Vigilance platform accessible by the public (French only).

Table F-1 shows the metrics computed for the discharge forecast at Carignan downstream of Saint-Jean-sur-Richelieu. MAE is the mean absolute error averaged for daily horizons. PBIAS is a measure of the relative bias of the forecasts. Alerting metrics refer to known flooding thresholds. An alert is based on the forecasting of the upward crossing of a threshold. Alerts can be successful, false (meaning no upward crossing was observed but was forecasted) or missed (meaning upward crossing was observed but was not forecasted).

Table F-1. Forecasting metrics for 030401_000 location at Carignan (2019-2020).

	Day 1	Day 2	Day 3
MAE (m^3/s)	66.2	91.0	102.9
PBIAS (%)	-0.7	-0.7	-0.3
Successful alert (%)	89	87	85
Missed alert (%)	11	13	15
False alert (occurrence)	0	3	2

The flood of 2019 was the most recent high flow event on the Richelieu River. Looking more closely at an issued forecast helps assess the quality of the product. Table F-2 presents metrics calculated on the five highest flow events of 2019 for all forecasting horizons combined (day 1, day 2 and day 3).

Table F-2. Forecasting metrics for 030401_000 location at Carignan (5 highest flow events of 2019).

	Complete Forecast
MAE (m3/s)	53
PBIAS (%)	-0.5

Figure F-4 shows the 2019 spring period (mid-April to early June) with five event forecasts, compared to observed discharge data. The slow discharge increase throughout the second half of April is well represented. An observed peak was missed in the forecast in the second half of April. These are high frequency events that are hard to consider. In fact, the ETS model described later in this report was developed specifically to improve the forecast for this kind of event. Forecasters are generally able to calculate manually the wind forecast effect based on empirical models and to integrate it in the forecast, as can be seen for the mid-May event, which exhibits good correspondence between forecast and observation.

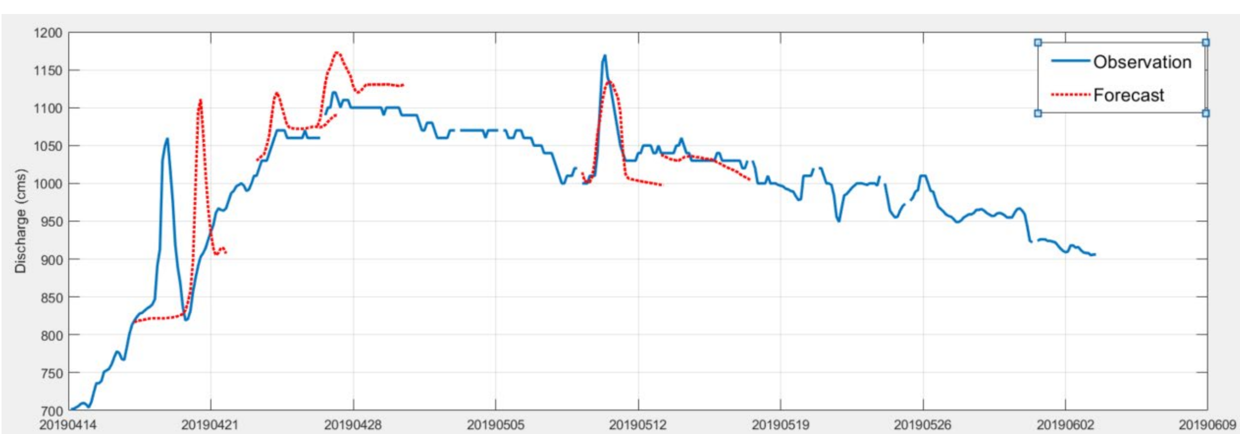


Figure F-4. 414 - High flow forecast (5 events) in 2019 .

APPENDIX G - Forecasting services and skill metrics for the United States

Within the United States, The National Weather Service (NWS) produces water forecasts (time series of flow and/or stage) through their regional River Forecast Centers (RFCs). There are 12 RFCs in the conterminous United States and a thirteenth RFC in Alaska. The Northeast River Forecast Center (NERFC) produces forecasts for over 200 discrete river locations across New England and in parts of New York (Figure G-1). Forecast locations are generally established to be coincident with USGS gauges (although they are not established at all gauges) and where communities have expressed and/or demonstrated a need for flood services. The river flows at most forecast locations are simulated with lumped watershed model algorithms. Due to the 6-hour time increments of available atmospheric forcing data for these models, and so that hydrologic peak responses can be captured, forecast locations are generally limited to places where the incremental drainage area at the point is 100 square miles or greater.

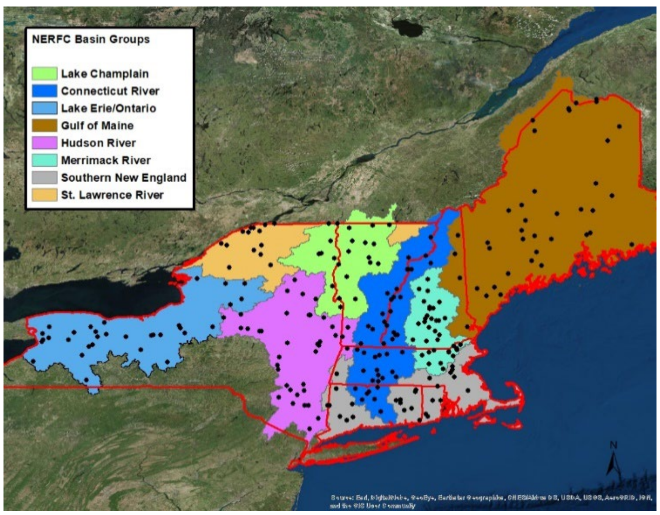


Figure G-1. NERFC Forecast Points (black) and hydrologic basins.

The NERFC forecast area includes the US part of the Lake Champlain-Richelieu River (LCRR) basin. Forecasts for the major tributaries within the LCRR basin are all established upstream to Lake Champlain so that the model-simulated inflows from each of those tributaries can then be used as inputs to a lake simulation. Figure G-2 shows the current forecast points in the basin and their contributing drainage areas, which define the lumped watersheds of the hydrologic models used by the NERFC.

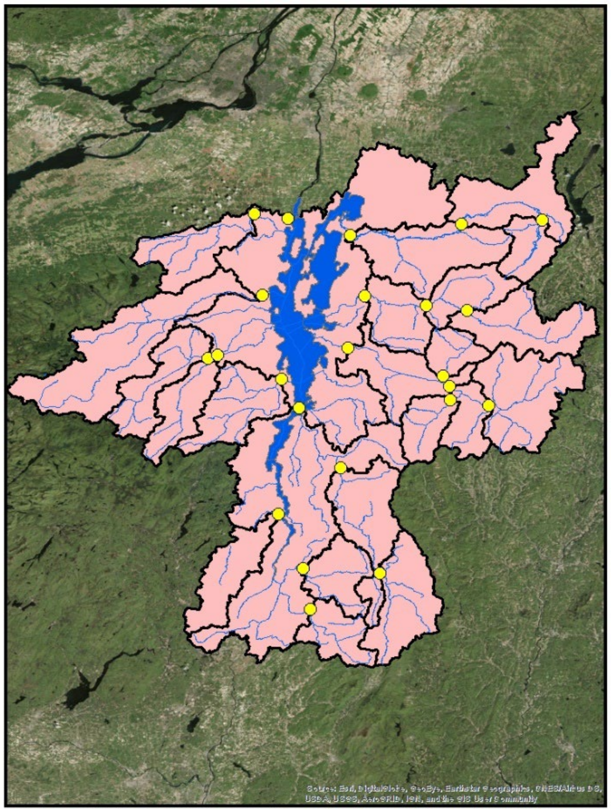


Figure G-2. Current LCRR forecast points (yellow) and their respective drainage areas.

The NWS uses a version of Deltares' Flood Early Warning System (FEWS) software to create these forecasts. The lumped watershed hydrologic algorithms that are employed for most forecast points are internal to the FEWS environment. Generally, the NWS version of FEWS (called CHPS – Community Hydrologic Prediction System) runs by (a) ingesting spatially and temporally distributed forcing information (e.g. precipitation, temperature), (b) establishing mean areal values of the forcings for each watershed and model time step, (c) executing the various algorithms for snow accumulation/ablation, soil moisture accounting, runoff and release of soil water to the land surface, and (d) routing of runoff and releases to downstream watersheds and water bodies.

CHPS also allows for different external standalone models to be used. When external models are employed, all model inputs are prepared within the CHPS environment and then passed to the external model. CHPS initializes the external model and then accepts output back from the model for display. As an example of an external standalone model integrated into CHPS, the NERFC uses the US Army Corps of Engineers' Hydrologic Engineering Center – River Analysis System (HEC-RAS) model to simulate Lake Champlain and the Richelieu River downstream to Saint- Jean-sur-Richelieu.

Deterministic forecasts are routinely made by NERFC hydrologists for each forecast point. Forecasters use a hands-on, interactive approach to adjust hydrologic model simulations to match the most recent five days of USGS gauge observations and then extend the water level forecast out five days into the future, based on weather model forecasts for precipitation, temperature, and soil moisture changes, and any upstream inflows.

An example of NERFC forecasts from 3/25/2021 is shown in Figure G-3. In the figure, observations are shown as black dots, the computer model simulations are shown as blue lines, and the forecasts (which typically blend the most recent observations with the simulations) are shown in magenta. Note that plots are provided for both Rouses Point (top) and Saint-Jean-sur-Richelieu (bottom). As noted above, the NERFC HEC-RAS hydraulic model domain extends from Lake Champlain down the Richelieu River to just past Saint-Jean-sur-Richelieu. This hydraulic model contains cross-sections of the lake and river, including the floodplain. Flows at each model cross-section are simulated, using the time-series of inflows from each upstream watershed contributing to the model. Then, at cross-sections where gauges exist, flow/elevation rating curves are used to translate the flows to elevations.

Forecast skill is retrospectively assessed monthly at the NERFC. This is done by automated execution of a script that compares each forecast value published with the ultimate observation that occurred for that time step. The script determines, for selected forecast points within a hydrologic basin and within a specified time frame (monthly), the number of comparisons that exist within the database. The script then calculates the mean error and mean absolute error for each of the forecast points. Table G-1 shows the script output for April 2019.

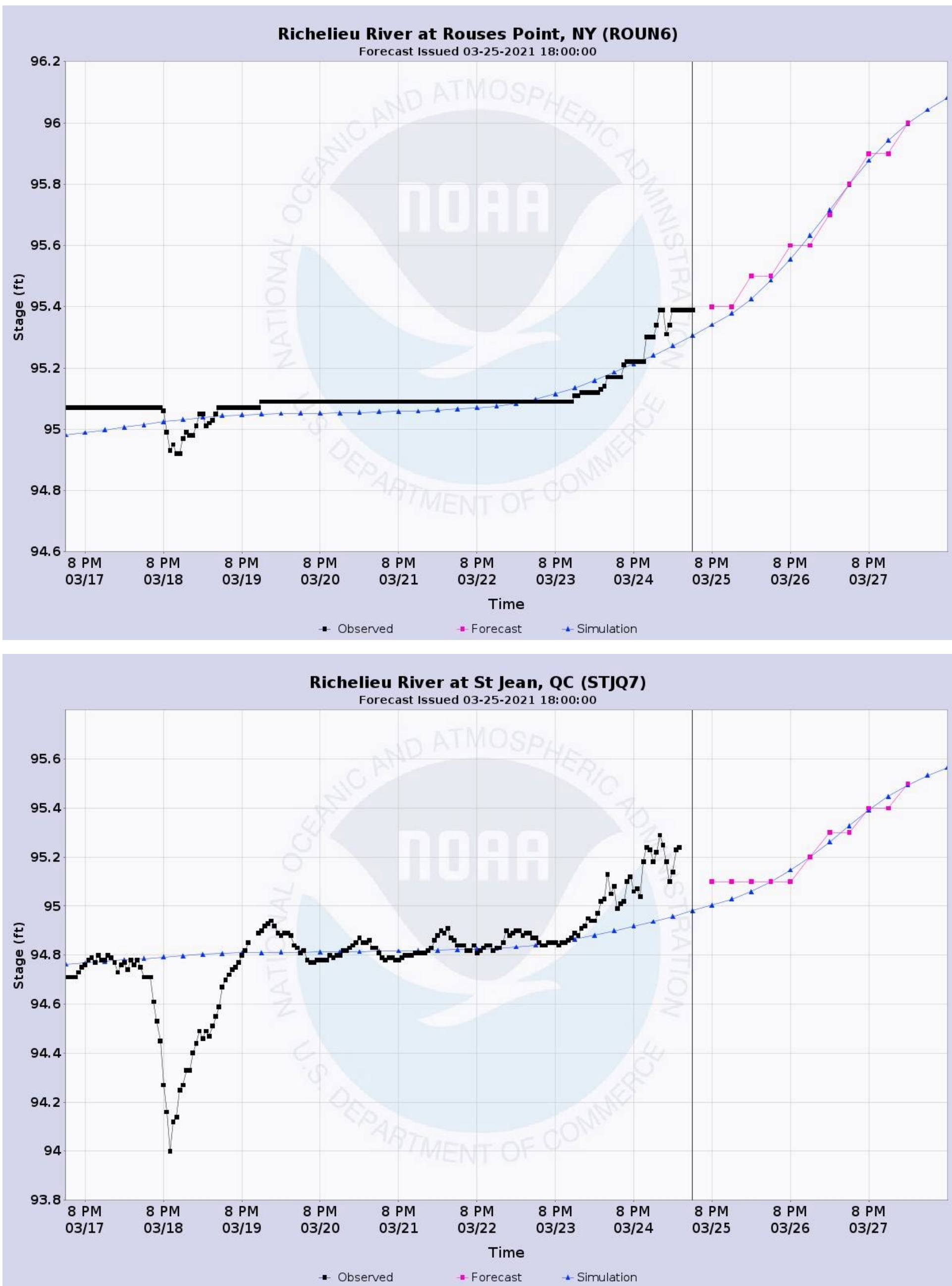


Figure G-3. NERFC hydrologic model forecast guidance for Rouses Point (top) and Saint-Jean-sur-Richelieu (bottom).

Table G-1. Monthly Mean Error and Mean Absolute Error for Lake Champlain Basin Forecasts (April 2019).

2019_Apr River Verifications ..... Lake Champlain				
Station ID	**Name**	**Number**	**MeanErr (ft)**	**MeanAbsErr (ft)**
CZRN6	Great Chazy River at Perry Mills NY	318	0.092	0.363
ASFN6	East Br. Au Sable River at Au Sable Forks NY	410	0.085	0.475
PBGN6	Saranac River at Plattsburgh NY	354	0.021	0.237
CARV1	Poultney River near Fair Haven VT	363	-1.504	1.707
CENV1	Otter Creek at Center Rutland VT	411	-0.19	0.674
GVVN6	Mettawee River at Middle Granville NY	366	-0.113	0.227
MONV1	Winooski River at Montpelier VT	411	0.282	0.488
MOOV1	Mad River at Moretown VT	423	-0.154	0.654
ESSV1	Winooski River at Essex Junction VT	437	0.152	0.832
JONV1	Lamoille river at Johnson VT	397	0.175	0.821
NTYV1	Missiquoi River at North Troy VT	409	-0.286	0.901
EBKV1	Missiquoi River at East Berkshire VT	385	-0.176	0.712
ROUN6	Lake Champlain at Rouses Point NY	381	-0.098	0.128
STJQ7	Richelieu River at St. Jean QC	394	-0.083	0.181

These mean errors and mean absolute error statistics are also generated for the subset of forecasts or observations that include flood threshold exceedances. Table G-2 shows the April 2019 results for Lake Champlain basin forecast points in this subset. Note that mean errors and mean absolute errors in this subset are generally greater than in the overall assessment shown in Table G-1. This is not unexpected, as forecast precipitation amounts can vary greatly with actual totals and many of the quick-responding forecast points can rapidly increase to exceed flood stage more quickly than forecasts can be updated. Even with this general trend, it is interesting to note that Lake Champlain at Rouses Point (ROUN6) flood exceedance forecasts were actually better than under overall conditions during April 2019. This may be due to the nature of the flooding that occurred in April 2019, which was driven primarily by a long, gradual snow melt that maintained minor flood status for over 30 days.

Table G-2. Mean Error and Mean Absolute Error for Lake Champlain Forecasts that Include a Flood Threshold Exceedance (April 2019).

..... FLOOD FORECAST BY FCST POINT			
Station ID	**Count**	**MeanErr (ft)**	**MeanAbsErr (ft)**
ASFN6	28	0.752	1.212
CENV1	74	-1.829	1.869
ESSV1	53	0.89	1.79
GVVN6	20	-1.471	1.493
JONV1	11	0.274	0.459
MOOV1	6	1.462	1.462
NTYV1	33	0.337	1.343
ROUN6	87	-0.046	0.064
STJQ7	55	0.125	0.19

.....Note: includes pairs where either fcst or observed above flood.....

These same statistics are also lumped together regionally and then broken down by (a) forecast lead time, (b) forecast issuance time (00z, 06z, 12z, 18z), and (c) stage amplitude change. In addition, the regional forecast-to-observation comparisons are also used to determine monthly Probability of Detection (POD) and False Alarm Rate (FAR). POD is a statistic that identifies, for all actual flood events over a period of time (e.g., one month), the percentage of time that the forecasted flood occurred. Conversely, FAR identifies, for all forecast flood events, the percentage of time that forecast floods did not materialize. POD and FAR are another set of statistics that are lumped together within the entire region for the monthly assessment. Table G-3 shows the NERFC POD and FAR results for April 2019.

Table G-3. Northeast Region Probabilities of Detection and False Alarm Rates for April 2019.

..... TABLEAU des prob. de détect.-TFA				
	Tous	**Jour 1**	**Jour 2**	**Jour 3**
Bons	2044	891	628	525
Manquées	676	177	274	225
Fausses alarmes	620	160	226	234
Prob. de détect	0.75	0.83	0.7	0.7
TFA	0.23	0.15	0.26	0.31

The NERFC also has other tools for assessing the skill of forecasts, such as the Interactive Verification Program (IVP), which can calculate various statistics for any temporal range of forecasts and observations at individual locations. Figure G-4 shows a typical comparison plot of the values from all 72-hour forecasts (i.e., 12 values per forecast) with the eventual observations that were made. This plot, for the Winooski River at Essex Junction, Vermont, is fairly typical of the spread between forecast and observed values that occurs for riverine locations. The start time of the window selected for the plot (8/1/2011) corresponds to the date when NERFC transitioned from 54-hour to 72-hour forecasts.

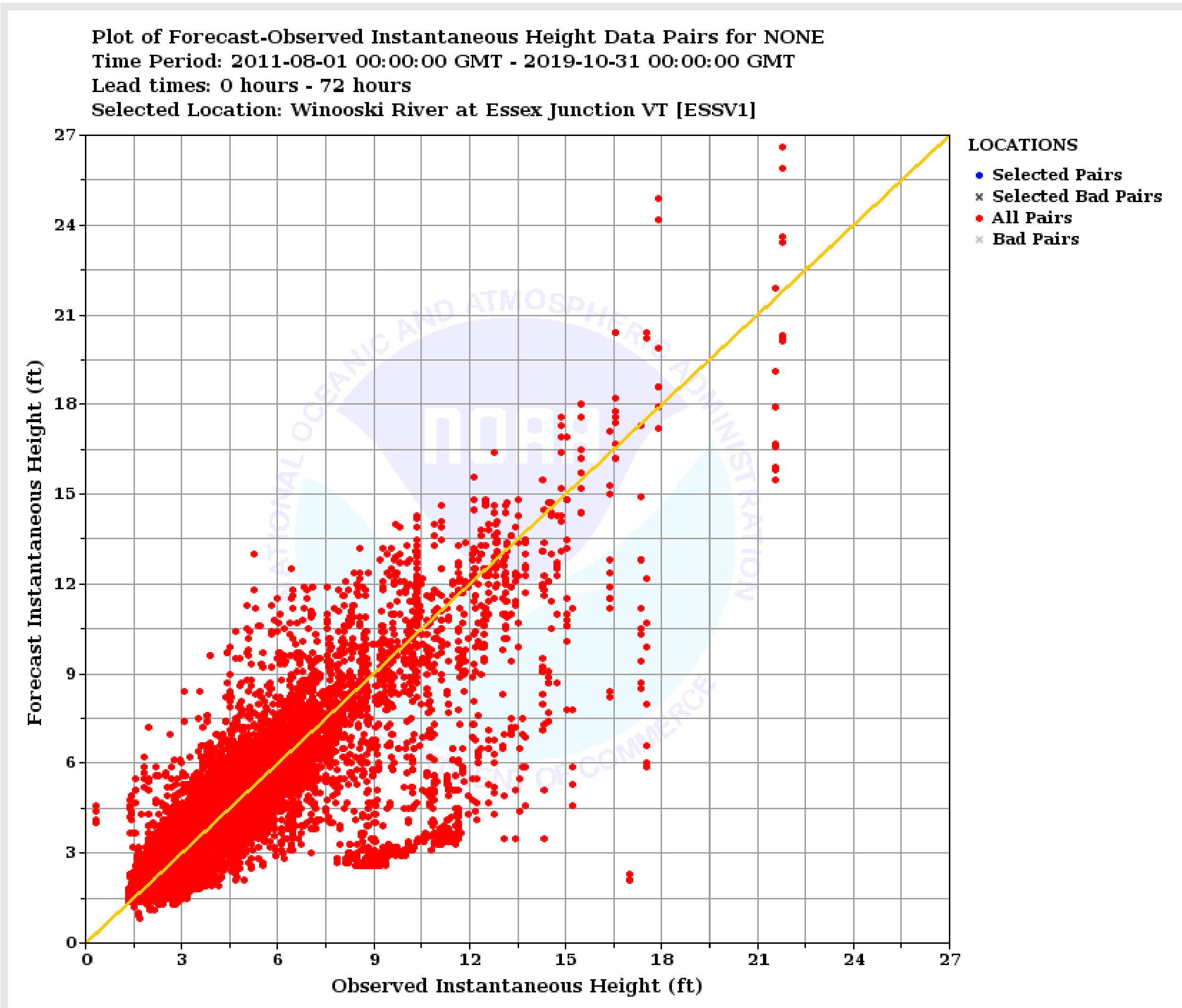


Figure G-4. Typical IVP Forecast vs. Observations Plot for 72-Hour Forecasts at a NERFC Riverine Location.

Contrasting with Figure G-4, Figure G-5 shows the same type of plot over the same period for the Rouses Point at Lake Champlain location. Forecasts and observations are more tightly correlated at this location, mainly due to the large volume of water in the lake that varies more gradually than typical river locations do. It should also be noted that the hydrologic model currently in use for the lake is the US Army Corps of Engineers' Hydraulic Engineering Center River Analysis System (HEC-RAS) model. While the Lake Champlain application of this cross-section-based model is relatively coarse, Figure G-5 shows that the model produces excellent results in predicting water surface elevations on the lake. The largest errors between forecast and observed values occur when wind effects perturb the water surface, as the version of HEC-RAS used for this simulation does not simulate wind. Table G-4 shows a comparison of basic statistics generated from Figures G-4 and G-5. Note the relative improvement in performance of the ROUN6 forecasts over the ESSV1 forecasts.

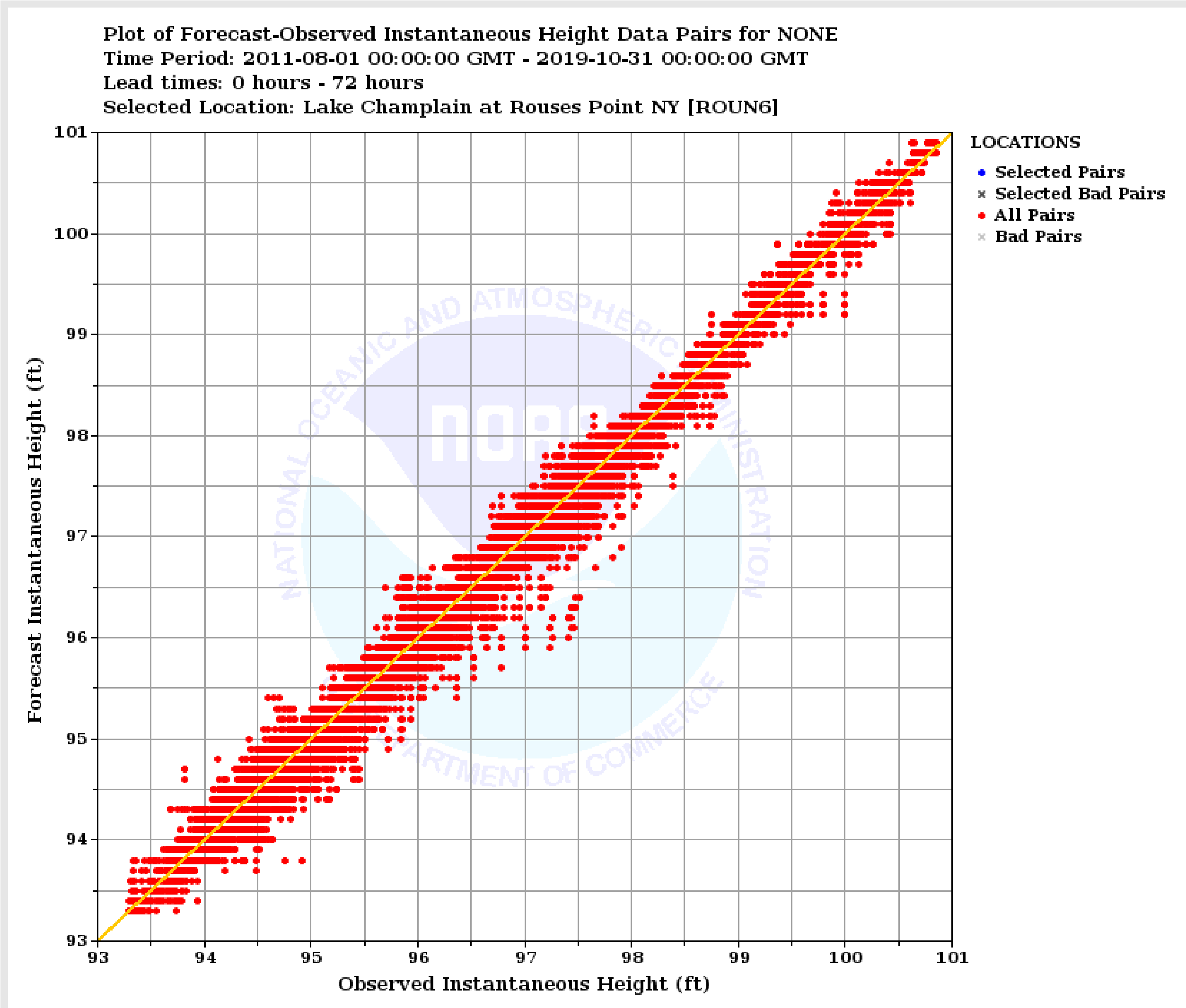


Figure G-5. Forecast vs. Observations Plot for 72-Hour Forecasts at Lake Champlain at Rouses Point (ROUN6).

Table G-4. Comparison of Essex Junction, VT and Rouses Point, NY Statistics (8/1/2011 – 10/31/2019).

Location	Mean Error (ft)	Mean Absolute Error (ft)	Root Mean Square Error (ft)	Maximum Error (ft)	Pearson Correlation r	Pearson Correlation r^2
ESSV1	-0.097	0.4615	1.057	14.9	0.851	0.724
ROUN6	-0.0098	0.0943	0.1395	1.41	0.996	0.992

The IVP also allows for the disaggregation of forecast statistics by forecast lead time. Since NERFC forecasts are issued for 6-hour intervals, this means that forecast statistics can be generated for each individual time step of the forecast, in order to assess progressive performance. Figure G-6 shows a histogram of the mean error (ME), mean absolute error (MAE), root mean square error (RMSE), and Pearson Correlation (CORR) statistics for Rouses Point, again generated for the period between 8/1/2011 and 10/31/2019, but disaggregated by forecast lead time. Table G-5 shows the raw values from this plot. Note that MAE and RMSE generally increase with lead time, as would be expected. However, the ME values do not show the same trend of increasing error with lead time, as values for hours 30 and 54 atypically show better agreement with observations than the values for hours 24 and 48, respectively. Other riverine locations in the LCRR basin do not exhibit this behavior. However, it should also be noted that all ME values in this plot are within +/-0.03 ft of observations.

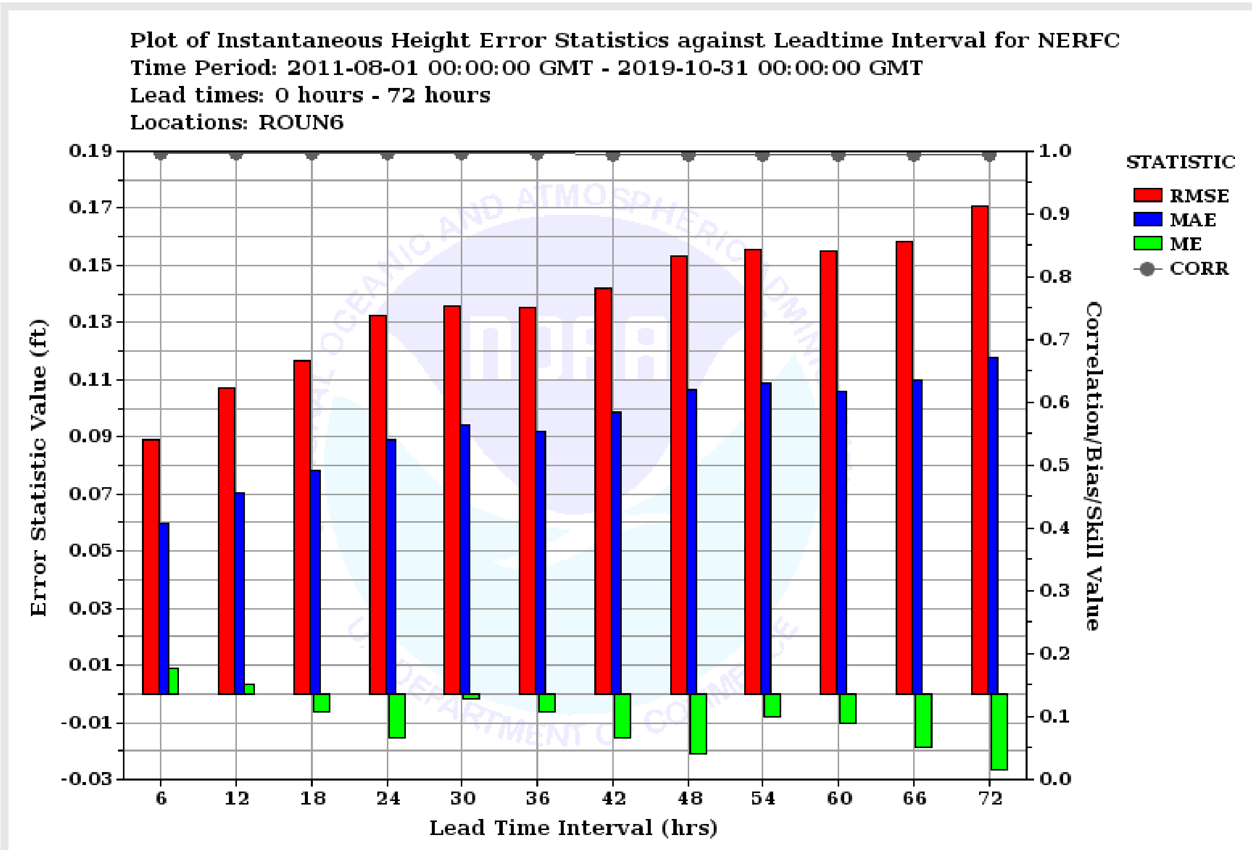


Figure G-6. Basic Performance Statistics for Lake Champlain at Rouses Point (ROUN6), Disaggregated by Forecast Lead Time.

Table G-5. Basic Performance Statistic Values for Lake Champlain at Rouses Point (ROUN6), Disaggregated by Forecast Lead Time.

Lead Time Interval (hr)	Mean Error (ft)	Mean Absolute Error (ft)	Root Mean Square Error (ft)	Pearson Correlation	
				r	r^2
6	0.009	0.060	0.089	0.998	0.997
12	0.003	0.070	0.107	0.998	0.995
18	-0.006	0.078	0.117	0.998	0.994
24	-0.016	0.089	0.132	0.997	0.993
30	-0.002	0.094	0.136	0.996	0.993
36	-0.006	0.092	0.135	0.996	0.993
42	-0.015	0.099	0.142	0.996	0.992
48	-0.021	0.106	0.153	0.996	0.991
54	-0.008	0.109	0.155	0.995	0.990
60	-0.010	0.106	0.155	0.995	0.990
66	-0.019	0.110	0.159	0.995	0.990
72	-0.027	0.171	0.171	0.994	0.989

NERFC Forecasts and Services

Once forecasts are generated at the NERFC, they are transmitted, via text product, to each of the eight WFOs in the region. The WFOs have the responsibility of publishing the forecasts and once published, individual hydrographs are generated for each point at the NWS Office of Water Prediction (OWP) Advanced Hydrologic Prediction System (AHPS) website (https://water.weather.gov/ahps/). The AHPS graphical interface shows a map with the maximum forecast flood category at each forecast point (Figure G-7). Selecting individual forecast points from this map leads the user to dedicated pages for the forecast points. The dedicated pages include the hydrograph for the site, as well as other site-specific information, such as a location map, historic flood information, flood category thresholds and exceedance probability plots. The AHPS site for Rouses Point on Lake Champlain is at https://water.weather.gov/ahps2/hydrograph.php?wfo=btv&gage=roun6 .

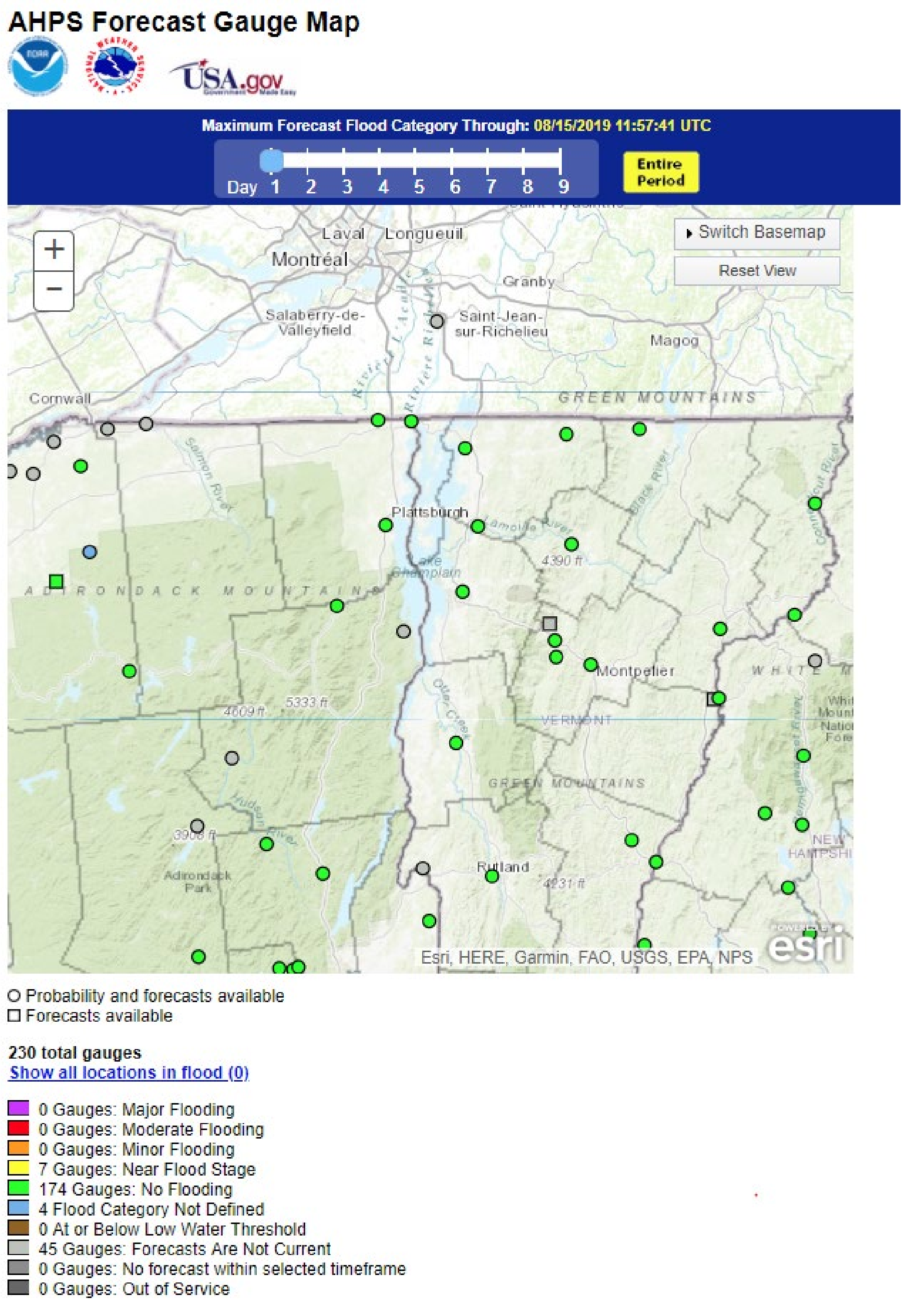


Figure G-7. NERFC AHPS forecast gauge map for Lake Champlain region.

Other graphical products that are generated at the NERFC include:

Daily Observed Precipitation Map – Each day NERFC forecasters quality-check hourly precipitation amounts from the previous 24 hours, as they were observed and recorded. The compiled precipitation data are summed at each gage location for the 6-hour periods ending at 00z, 06z, 12z, and 18z. Distributed precipitation grids are created for each 6-hour period by interpolating between the gage location values. Finally, a daily total grid is created by summing the four 6-hour grids. Figure G-8 shows an example of a daily total precipitation graphic. NERFC archives each of these daily grids and also creates graphics for running 3-day and 5-day totals. These graphics can be found at https://www.weather.gov/nerfc/ObservedPrecipitation.

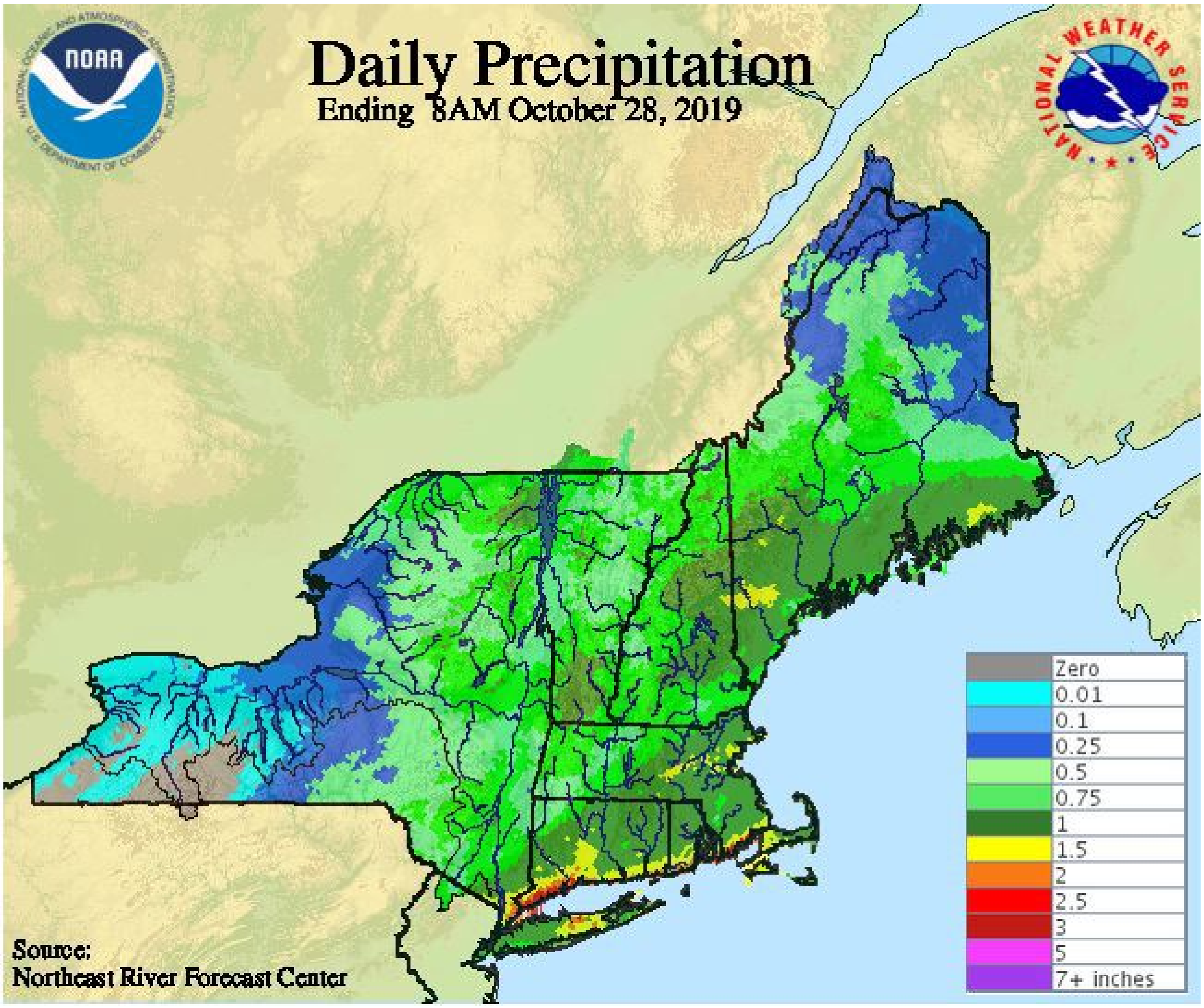


Figure G-8. NERFC 24-Hour Observed Precipitation.

Quantitative Precipitation Forecast (QPF) – NERFC forecasters review the most recent atmospheric models in order to develop future precipitation forcings for the CHPS hydrologic models. These QPF grids typically extend 72 hours into the future, but are sometimes extended up to 96 hours when an impending event will overlap the 72–96-hour time frame. NERFC forecasters refresh the QPF grids three times daily (four times when flooding necessitates overnight staffing). As with the observed precipitation grids discussed above, the QPF grids are developed for each 6-hour increment ending at 00z, 06z, 12z, and 18z. Then a summary QPF grid for the entire precipitation forecast period is developed and published. Figure G-9 shows an example of a 72-hour QPF graphic. This graphic, as well as each incremental 6-hour QPF grid that composes it, can be found at https://www.weather.gov/nerfc/ForecastPrecipitation.

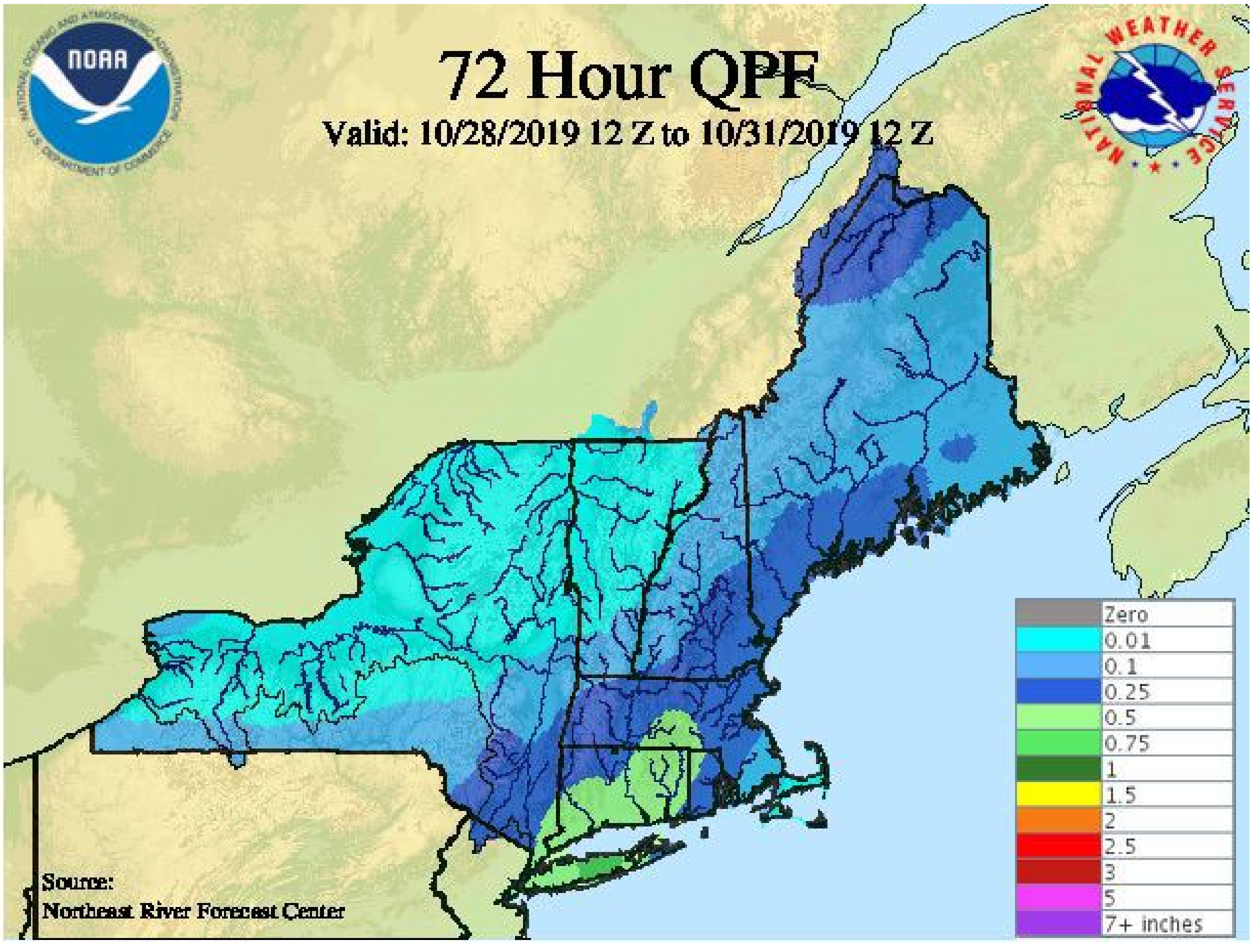


Figure G-9. NERFC 72-Hour Forecast Precipitation.

5-Day Significant River Flood Outlook Product (FOP) – After forecasts are issued each day, the lead forecaster on duty assesses where any significant (i.e. Moderate or Major) flooding is occurring, likely, or possible, and develops a flood outlook map, or FOP, as a quick regional reference for NERFC's partnering entities and the general public. For most days, this graphic identifies that "No Significant River Flooding Is Expected". However, when flooding is imminent or expected, the graphic can be populated for a number of consecutive days. An example of a populated FOP graphic is shown in Figure G-10. This graphic is updated daily and can be found at https://www.weather.gov/nerfc/fop .

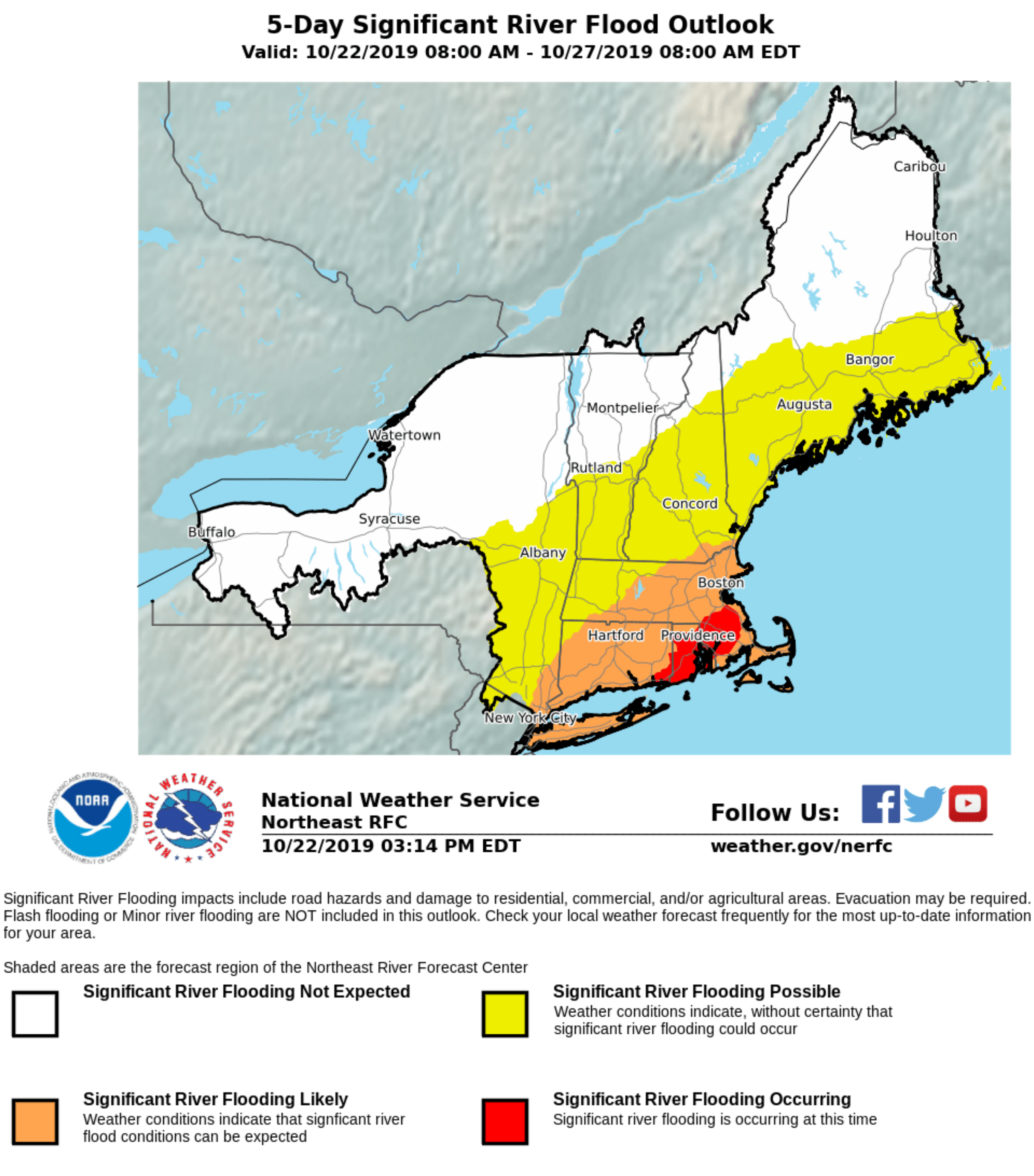


Figure G-10. NERFC Flood Outlook Product (sample).

Flash Flood Guidance – In addition to the river forecasts generated daily, NERFC forecasters also generate grids of Flash Flood Guidance three times daily. These grids, which are generated for 1-hour, 3-hour, and 6-hour guidance, provide estimates for the depths of rainfall that would result in flash flooding. The algorithms for these calculations take into consideration, for each 4-km grid cell in the region, modeled soil moisture content, hydrologic conductivity of the soil, and percent of land use impervious cover. Graphics for these flash flood guidance grids are updated at https://www.weather.gov/nerfc/ffg as they are generated. Figure G-11 shows an example of a 1-hour flash flood guidance grid.

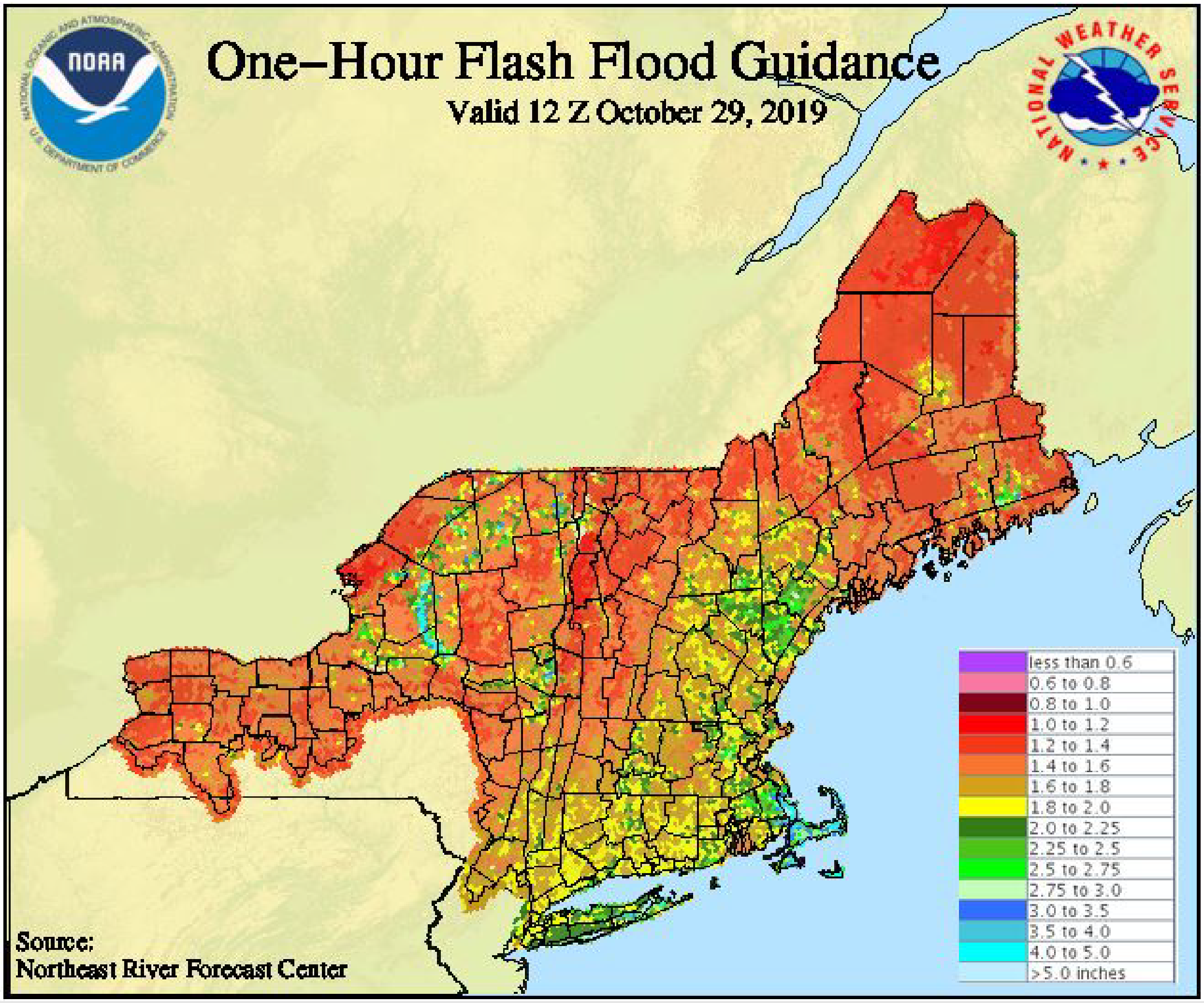


Figure G-11. NERFC 1-Hour Flash Flood Guidance.

Graphical Hydrometeorological Discussion (HMD) – NERFC forecasters generate a daily graphical briefing for distribution on various social media platforms. This product provides a brief summary of the main points of the day's forecasts. In addition to this graphic's issuance to Twitter and Facebook, it can also be found on the NERFC website at https://www.weather.gov/nerfc/briefings. Figure G-12 shows an example of a daily Graphical HMD.

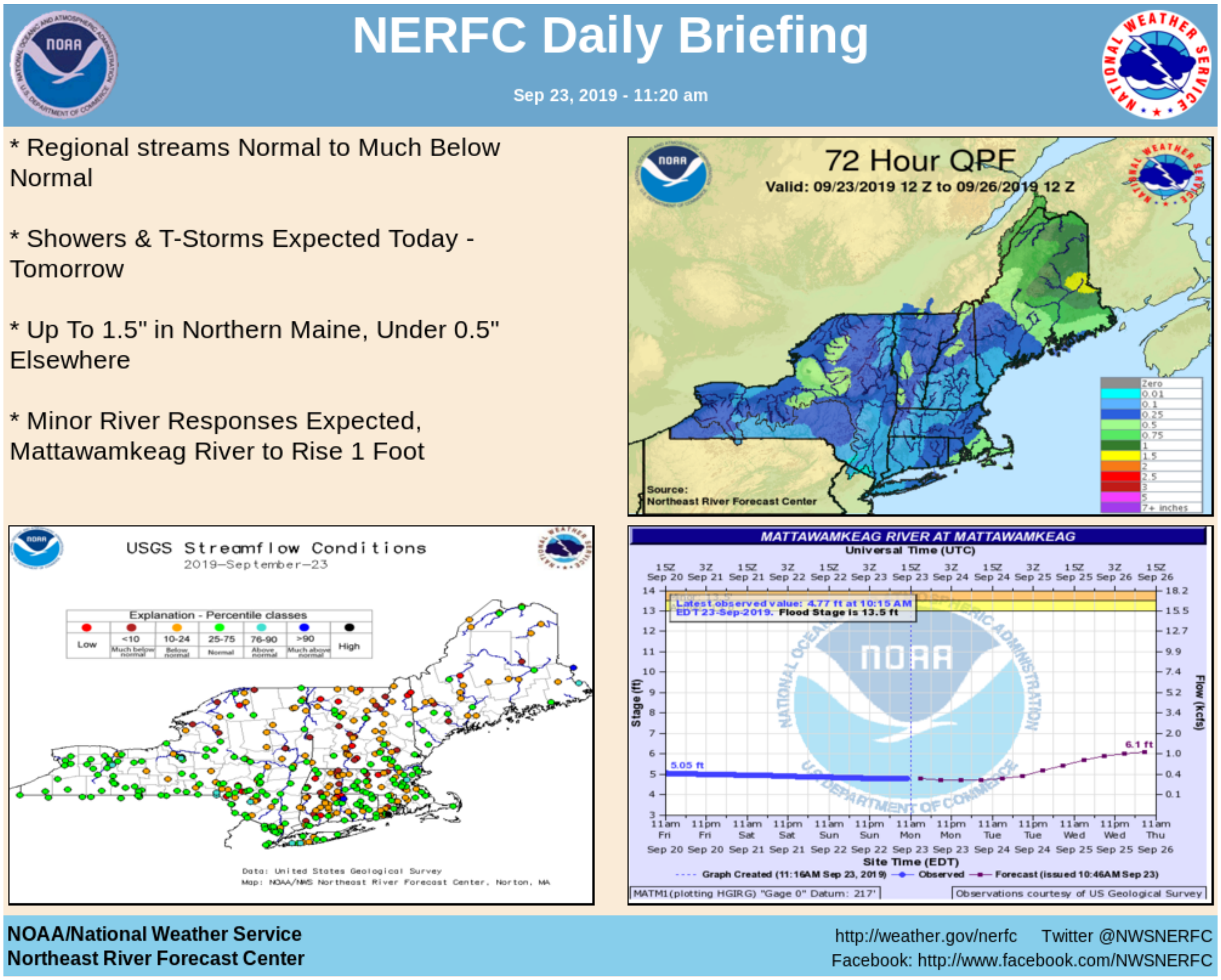


Figure G-12. NERFC Graphical Hydrometeorological Discussion.

Snow Maps – During the snow season (October 1 – May 31), NERFC forecasters generate maps of daily snowfall and current snow depth. These maps are refreshed daily and are located on the NERFC website at https://www.weather.gov/nerfc/snow. Figure G-13 shows examples of the daily snowfall and current snow depth grids.

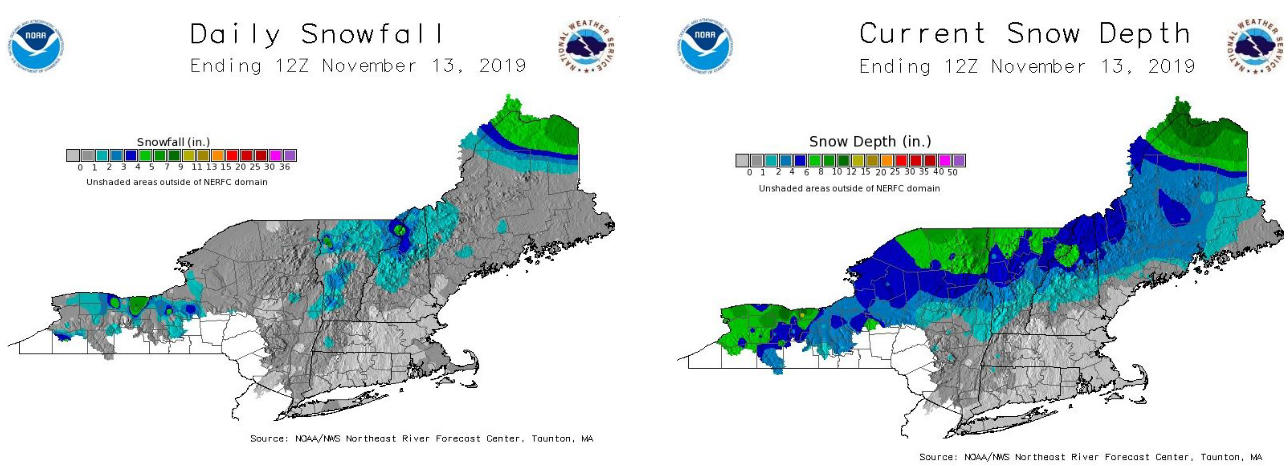


Figure G-13. NERFC Daily Snowfall and Current Snow Depth Grids.

Model Ensemble Graphics – In addition to providing daily deterministic forecasts, NERFC forecasters generate supplemental ensemble graphics for each of the NERFC forecast points. These three graphics provide longer term probability information for each of the forecast points and can be found on the AHPS website for each individual forecast point (e.g. specified above for Rouses Point, NY) by selecting the Probability Information tab just above the forecast hydrograph for the point. The three graphics are described as follows:

(a) Exceedance probability plots are created for each forecast point on a weekly basis. The simulations run for these plots extend for 90 days into the future. The plots show two different ranked exceedance probability curves: (1) a historical simulation ranking the maximum values from the upcoming 90-day window in each individual year of the long-term historical record (59 years), and (2) an ensemble of conditional simulations using current weather and hydrologic conditions, along with a subset of years from the historical record which are similar to the expected weather pattern as indicated in the long-term weather (i.e. climate) forecast. Figure G-14 shows an example of an Exceedance Probability plot created for the Rouses Point, New York forecast point on Lake Champlain.

(b) Weekly Chance of Exceeding Levels plots are created for each forecast point on a weekly basis. As with the exceedance probability plot, this plot provides supplemental forecast information for 90 days into the future. The plot takes the data from the conditional simulations discussed above and, rather than displaying the maximum value from each simulation run of the ensemble, considers the distribution of all values within each 7-day period of the entire upcoming 90-day interval. The values within each consecutive 7-day period are then plotted in a stacked histogram format, with each value falling within a pre-defined range of probability. This plot can be helpful in estimating when, within the next 90 days, any potential flooding threat may occur. Figure G-15 shows an example of the Weekly Chance of Exceeding Levels plot for the Rouses Point, New York forecast point on Lake Champlain.

(c) Experimental plots of 10-day River Level Probabilities are generated daily for each forecast point. The plots are part of the NWS Hydrologic Ensemble Forecast System (HEFS), which uses a combination of physically-based and statistical modelling to create an ensemble of simulation runs. Current hydrologic conditions, as defined by the RFC deterministic forecasts, are used along with atmospheric forcings from the Global Ensemble Forecast System (GEFS) and the Climate Forecast System (CFS) and various hydrologic parameter adjustments, to create the ensemble members. The experimental probability plots attempt to convey forecast uncertainty for the immediate 10-day forecast period through the use of bounding envelopes characterizing all simulation traces that fall within the 25th – 75th, 10th – 90th, and 5th – 95th percentiles of the ensemble simulations. Figure G-16 shows an example of a 10-Day River Level Probabilities plot for the Rouses Point, New York forecast point on Lake Champlain.

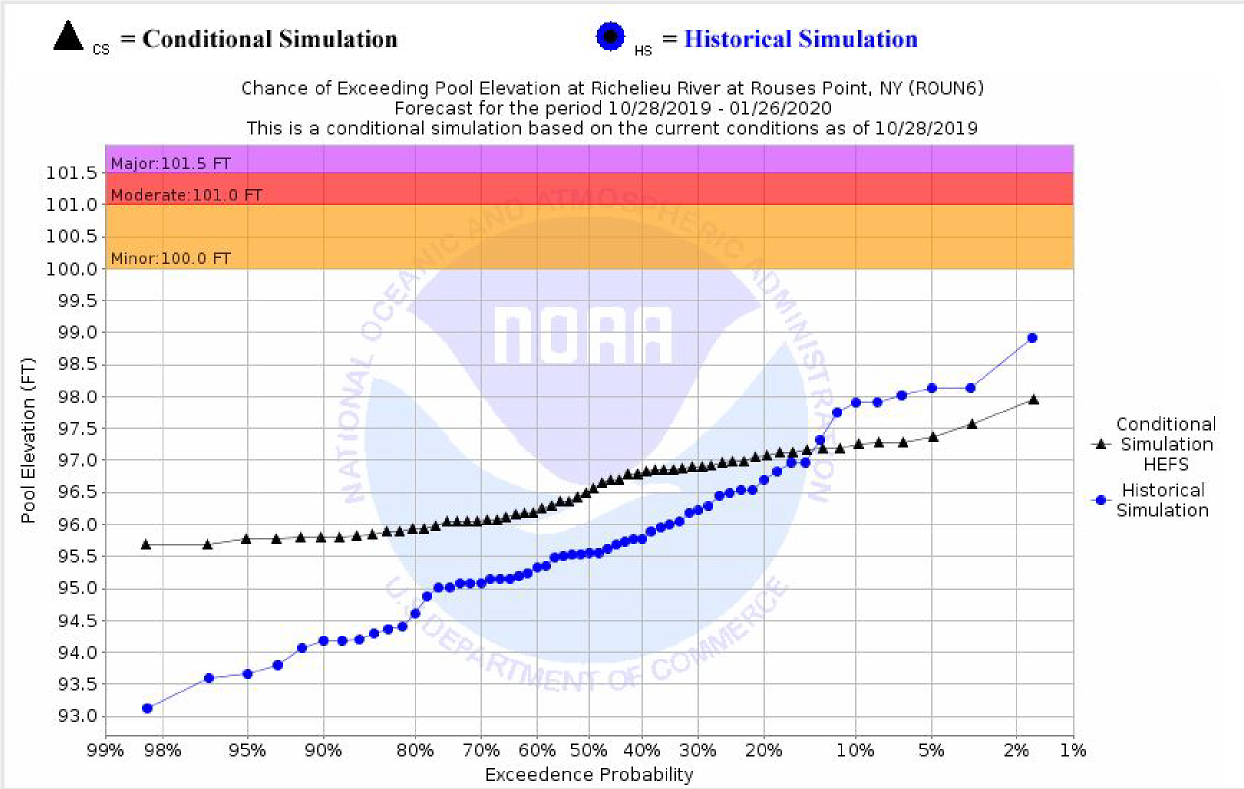


Figure G-14. NERFC Weekly Exceedance Probability Plot.

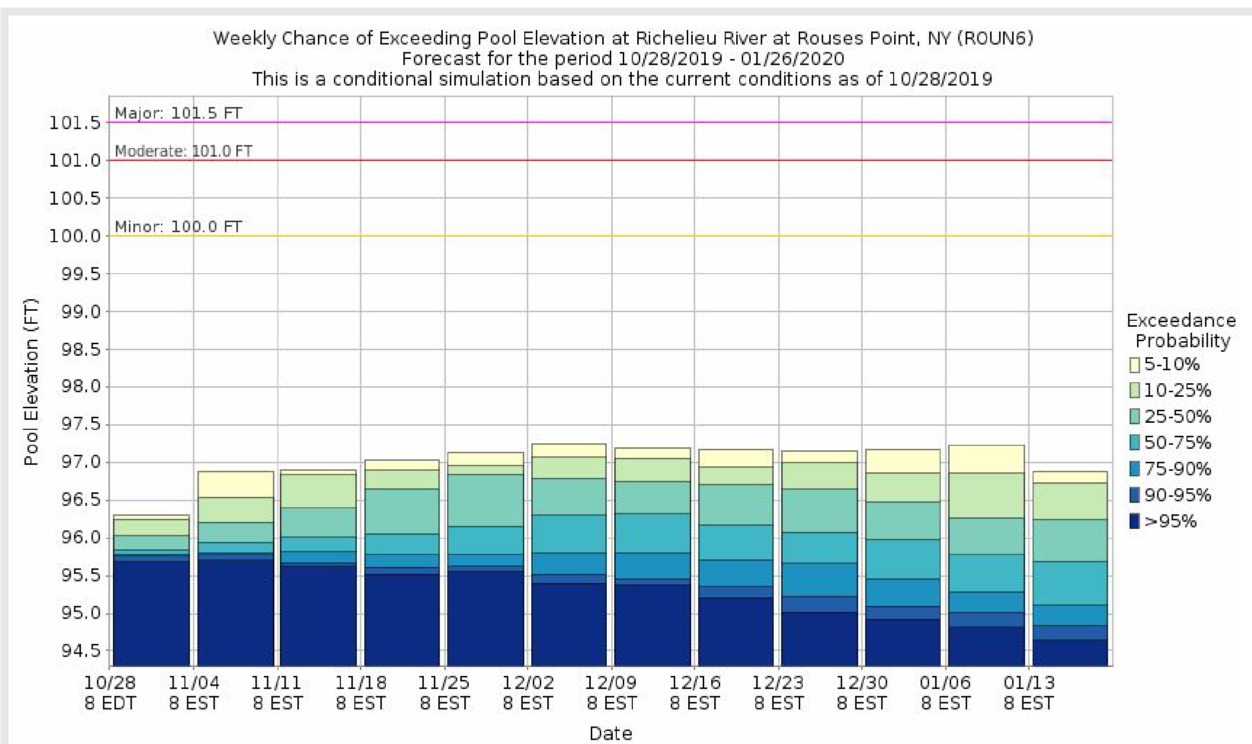


Figure G-15. NERFC Weekly Chance of Exceeding Levels Plot.

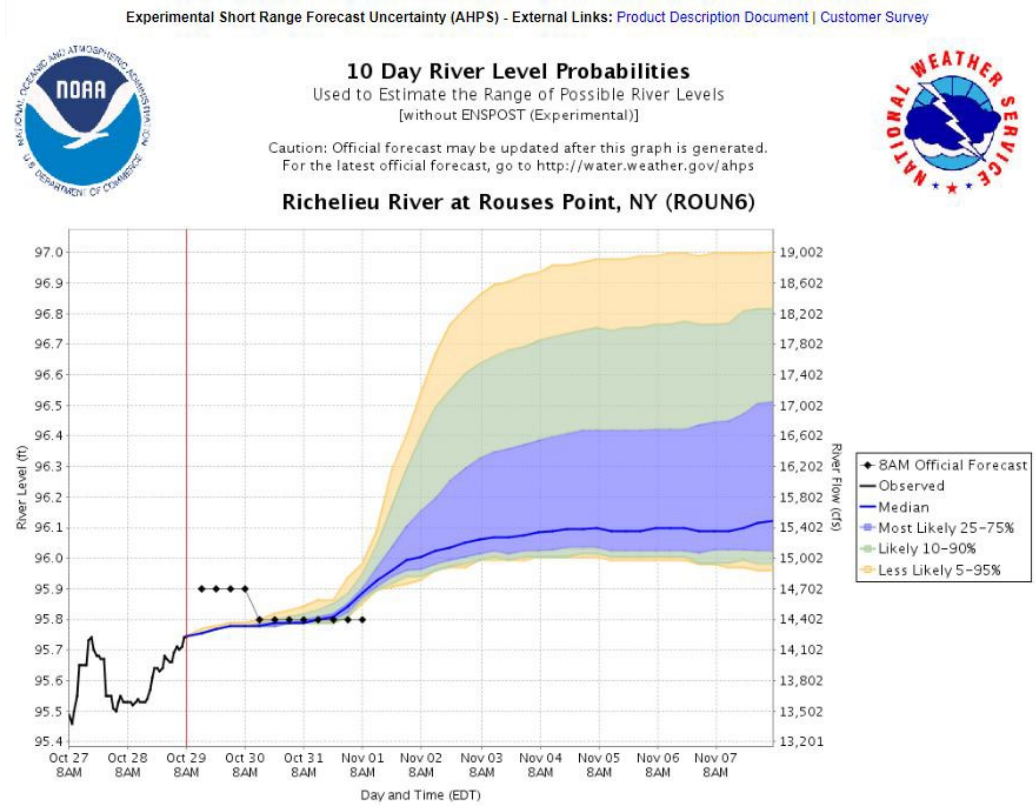


Figure G-16. NERFC Daily 10-Day River Level Probabilities Plot.

Weather Forecast Offices

Once all NERFC hydrologic forecasts (including for Lake Champlain) are complete, typically between 11 AM and 12 PM daily, the NERFC sends the resultant time series of flows and/or stages to the eight Weather Forecast Offices (WFOs) in the northeast region. These offices include the Burlington, Vermont office (BTV) for the Lake Champlain basin. The NWS WFOs are responsible for publishing products including weather and water warnings and watches throughout their individual service areas. Further information on NWS flood products is available online at https://www.weather.gov/safety/flood-products.

The WFOs review NERFC's daily hydrologic forecasts and then either publish them as is or make slight modifications before publication. Most modifications occur when (a) river gauges are affected by ice and natural flows are not matching up with observations, or (b) the forecast indicates that water levels will fluctuate about a flood threshold (e.g. Minor, Moderate, Major flood) – in this case, the WFO may decide to keep the forecast just at or above the threshold, so as to aid communication of the hazard (e.g., to avoid having to take down the flood watch and then re-issue it shortly thereafter).

Based on these hydrologic forecasts, NWS WFOs disseminate several products to inform their stakeholders of water levels in Lake Champlain. A daily river and lake forecast text product (Figure G-17) is created with the stage forecasts for all points in the WFO's area of responsibility. When stage forecasts reach predetermined action levels computed by NWS hydrologists, (i.e., action stage, flood stage, moderate, major), the WFO can issue flood watches, warnings (Figure G-18) and follow-up flood statements (Figure G-19).

```
Daily River and Lake Summary
National Weather Service Burlington VT
1040 AM EDT Mon Aug 5 2019

Go to www.weather.gov/btv/rivers for the latest observed and forecast
river levels. Some river levels are affected by power generation.
River forecasts represent natural flow and are not adjusted for ice.

.B BTV 0805 DC19080510 DH12/HG/DRH+24/HGIFF/DRH+36/HGIFF/DRH+48/HGIFF


:    Station          Flood   7AM    24-Hr   7AM      7PM      7AM
: ID       Name       Stage  Stage  Change Forecast Forecast Forecast
:                                            Tue      Tue      Wed
:Lake Champlain
ROUN6: Rouses Point  100.0: 95.40 /: -0.02:  95.40 / 95.40 / 95.40 /
:
:Great Chazy River
CZRN6: Perry Mills     9.0:  1.60 /:  0.06:   1.60 /  1.50 /  1.50 /
:
:Saranac River
PBGN6: Plattsburgh     9.0:  2.97 /: -0.02:   3.00 /  3.00 /  3.00 /
:
:East Branch Ausable River
ASFN6: Ausable Forks   7.0:  1.03 /: -0.03:   1.00 /  1.00 /  1.00 /
:
```

Figure G-17. Daily River and Lake Summary Forecast from WFO Burlington.

```
FLWBTV
BULLETIN - EAS ACTIVATION REQUESTED
Flood Warning
National Weather Service Burlington VT
1244 AM EDT Sun Apr 21 2019

...The National Weather Service in Burlington has issued a Flood
Warning for Lake Champlain in New York and Vermont...

  Lake Champlain At Rouses Point

PRECAUTIONARY/PREPAREDNESS ACTIONS...


Safety message...

Persons with interests in flood prone areas along Lake Champlain
should take action to protect their property. The combination of wind
and wave action will enhance flood effects on windward facing shores,
and may cause additional damage to shoreline roads and low lying
areas.

Stay tuned to developments by listening to noaa weather radio, or by
visiting our web site at: weather.gov.

&&

NYC019-031-115-VTC001-007-011-013-021-220443-
/O.NEW.KBTV.FL.W.0017.190421T1800Z-000000T0000Z/
/ROUN6.1.ER.190421T1800Z.190424T0000Z.000000T0000Z.NO/
1244 AM EDT Sun Apr 21 2019

The National Weather Service in Burlington has issued a

* Flood Warning for
  The Lake Champlain At Rouses Point.
* from this afternoon until further notice...Or until the warning is
  cancelled.
* At 12:00 AM Sunday the stage was 99.8 feet.
* Flood stage is 100.0 feet.
* Minor flooding is forecast.
* Forecast...Rise above flood stage by Sunday afternoon and continue
  to rise to near 100.4 feet by Tuesday evening. Additional rises are
  possible thereafter.
* Impact...At 100.0 feet...Water begins to enter some lake front
  properties. Water also begins to threaten low lying roads, piers,
  and docks. Wave action can compound flooding on windward facing
  shorelines. Water will threaten the Burlington waterfront at
  Perkins Pier and the King Street ferry dock.

&&

LAT...LON 4501 7347 4501 7306 4361 7328 4360 7348
```

Figure G-18. Flood Warning for Lake Champlain from WFO Burlington.

```
FLSBTV
Flood Statement
National Weather Service Burlington VT
1158 AM EDT Mon Apr 22 2019

...The Flood Warning continues for Lake Champlain...
  Affecting the Lake Champlain shoreline counties in New York...
  Clinton...Essex...Washington and in Vermont...Addison...
  Chittenden...Franklin...GrandIsle...Rutland

PRECAUTIONARY/PREPAREDNESS ACTIONS...

Persons with interests in flood prone areas along Lake Champlain
should take action to protect their property. The combination of wind
and wave action will enhance flood effects on windward facing shores,
and may cause additional damage to shoreline roads and low lying
areas.

&&

NYC019-031-115-VTC001-007-011-013-021-231657-
/O.CON.KBTV.FL.W.0017.000000T0000Z-000000T0000Z/
/ROUN6.1.ER.190421T1115Z.190425T0000Z.000000T0000Z.NO/
1158 AM EDT Mon Apr 22 2019

The Flood Warning continues for
  The Lake Champlain At Rouses Point.
* At 11:00 AM Monday the stage was 100.3 feet.
* Flood stage is 100.0 feet.
* Minor flooding is occurring and Minor flooding is forecast.
* Forecast...The lake level will continue rising to near 100.6 feet
  by Wednesday evening. Additional rises may be possible thereafter.
* Impact...At 101.0 feet...Flooding affects low lying roads and
  properties, and wind and wave action can compound flooding on
  exposed shorelines. Portions of the Burlington waterfront will
  flood, including the King Street ferry dock and Perkins Pier.

&&

LAT...LON 4501 7347 4501 7306 4361 7328 4360 7348
```

Figure G-19. Flood Statement (Follow-up to Initial Flood Warning) from WFO Burlington.

When the WFOs publish their forecasts, they are also sent to the NWS Office of Water Prediction (OWP), which displays them on the Advanced Hydrologic Prediction Service (AHPS) web pages. These pages show a hydrograph with the most recent three days of observations at each gauge and the first three days of the forecast (Figure G-20). They also commonly show historic crest information, a location map for the gauge, and gauge-specific descriptive flood information for incremental elevations above the flood stage. For reference, the Rouses Point AHPS page is located at https://water.weather.gov/ahps2/hydrograph.php?wfo=btv&gage=roun6 .

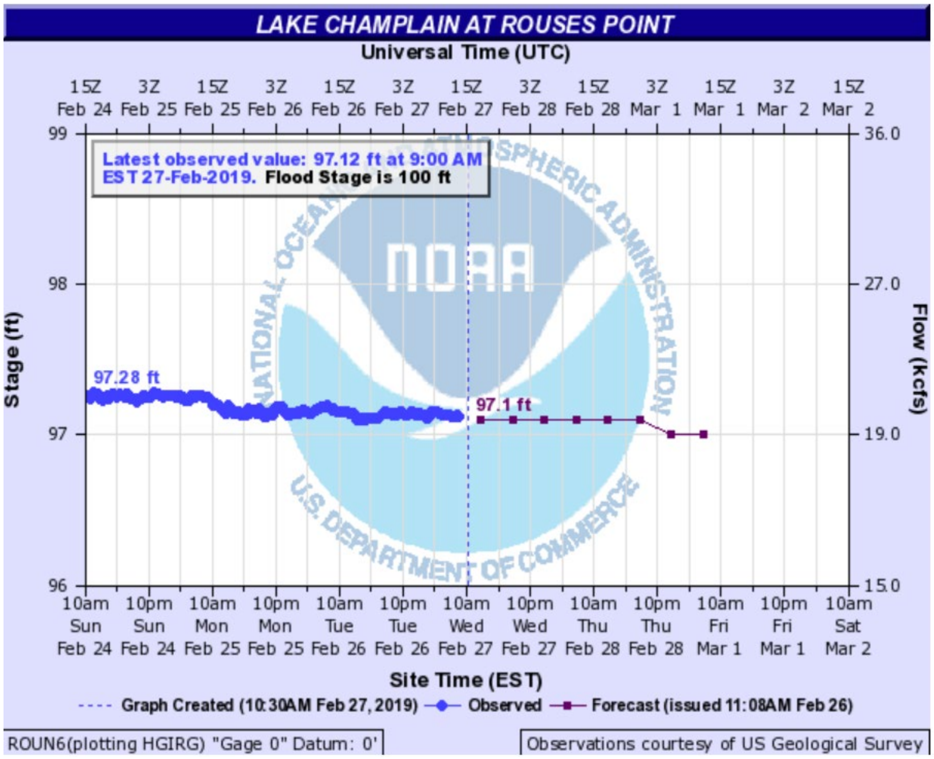


Figure G-20. AHPS site for Rouse's Point.

The information for the Rouses Point hydrograph is also available in an XML format. Note that the forecast information is toward the bottom of the XML file, just below the </observed> line. This can be accessed by clicking on the XML button just below the hydrograph on the page listed above, or directly (e.g., https://water.weather.gov/ahps2/hydrograph.php?wfo=btv&gage=roun6&output=xml). However, no flood mapping is presently available for NWS Lake Champlain forecasts.

In addition to the routine issuances of Lake Champlain lake level forecasts, WFO Burlington issues Flood Watches and Flood Warnings for the entire stretch of Lake Champlain in New York and Vermont when the lake level is forecast to exceed its 100 ft NGVD 29 flood stage; these are updated daily at midday until the lake level drops below flood stage.

WFO Burlington also increases its decision support services immediately prior to and during lake flooding by providing Situational Awareness briefs via e-mails to decision makers, including the 3-day deterministic forecast as well as potential future trends and impacts based off longer-term probabilistic and exceedance guidance. If lake levels are expected to approach or exceed major flood (101.5 ft NGVD 29) and/or strong winds are expected to cause a significant seiche or wave action that would be impactful, additional support to decision makers would occur.

INTERNATIONAL JOINT COMMISSION • COMMISSION MIXTE INTERNATIONALE

1909