A Strategy for Addressing Climate Uncertainty Affecting Lake Champlain-Richelieu River Flooding

International Lake Champlain - Richelieu River Study

A REPORT TO THE INTERNATIONAL JOINT COMMISSION

Submitted by

Bill Werick

Flood Management and Mitigation Measures
Technical Working Group

May 2022

ACKNOWLEDGMENTS

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

EXECUTIVE SUMMARY

This report describes the strategy being used to take climate change into account when the Lake Champlain-Richelieu River Study Board (Board) makes its findings and recommendations regarding flood mitigation.

STUDY FOCUS

The strategy follows International Joint Commission guidelines for planning for the impacts of climate change, most notably in that it follows a process called "decision scaling." Decision scaling goes beyond making climatological projections, which are inevitably uncertain, to consider how to make robust decisions despite that uncertainty. Some of the work described in the strategy has already been done, while some is still underway.

APPROACH

The study experts will pursue decision scaling from four perspectives, applying those perspectives individually for some purposes and considering them simultaneously for others. The first perspective is statistical. The study experts will develop three different stochastic net basin supply (NBS) sets using three different assumptions about the patterns in the historic supplies that help predict patterns in future supplies. The supplies can be translated into water levels, flows, flooded extent and depths, and damages when used as inputs to a series of computer models. The stochastic results will be especially helpful in estimating benefit-cost ratios for potential structural solutions.

The second perspective is to formulate a Probable Maximum Flood (PMF). The historic 2011 flood was the product of three fairly independent factors: heavy snowpack, early spring temperatures that preserved much of that snow, and heavy precipitation in March and April. The PMF analysis considers the possibility that each of those three factors could be greater individually and could then act together to create a larger flood than in 2011. PMF and similar concepts have been used in the past to avoid flood project designs that could induce catastrophes if a flood project were to fail. In addition, this concept could be useful in delineating boundaries for floodplain management.

The third perspective is referred to as stress testing in which average annual temperature and precipitation amounts are incrementally increased and a "weather generator" is used to create inputs to a basin model, thus producing Net Basin Supplies to Lake Champlain. The flood levels and damages of these increases can thus be calculated. These results can then be easily compared to a wide range of precipitation and temperature projections from many climate models, allowing the study experts to map the range of flood impacts projected by those models.

The fourth perspective is to create basin model inputs from specific Global Climate Models and Regional Climate Model projections over time, producing Net Basin Supplies that might occur under different emission scenarios at different times in the 21st century.

The four perspectives will be used together to challenge and refine findings from the individual perspectives about likely Lake Champlain levels in the 21st century. Multiple perspectives will be applied to inform the Board's recommendations for flood response plans and floodplain management. The experts have agreed to share their internal debates on technical issues, assumptions, and modeling choices. The final climate report due later this year will have short summaries of the explorations of the team on these issues so that readers, including researchers on other climate studies, can benefit from the debate and deliberation.

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

LIST OF TABLES

1 INTRODUCTION

This report lays out a proposed strategy for how the Lake Champlain-Richelieu River (LCRR) Study Board should consider climate variability and change in making its findings and recommendations regarding flooding on Lake Champlain and the Richelieu River. Some work described in this strategy has already been completed and more work is underway; this is not a progress report, but it does include some of the work-in-progress when it helps clarify the strategy. Reports on the results from applying these methods will be completed later in 2021.

The key question for the Study Board is: how should we prepare for the flooding along the coast of Lake Champlain and down the Richelieu River that will occur in the next few decades?

Preliminary findings suggest the region should prepare for generally lower water levels and the problems associated with low water levels based on climate analyses.

After a record LCRR flood in 2011, the governments of Canada and the United States gave a reference[1] to the International Joint Commission (IJC) to provide recommendations on what should be done to mitigate the flooding issue. The IJC appointed the International Lake Champlain Richelieu River Study Board in 2017 to oversee and manage the study looking into the causes, impacts, risks, and solutions to flooding in the International Lake Champlain and Richelieu River basin. Water flows into Lake Champlain at different rates every year, generally peaking in spring. Floods are typically the result of sustained high tributary flows into the lake in April and May. The flow rates in those months vary from year to year due to the natural variation in a stationary climate, quasi-periodic wet-dry cycles and climate change. The key question for the Study Board is: how should we prepare for the flooding along the coast of Lake Champlain and down the Richelieu River that will occur in the next few decades? The proposed strategy described herein is designed to support the best possible answer to that question despite the irreducible uncertainty in estimates of the severity and chance of future flooding. Preliminary findings suggest that the region should prepare for generally lower water levels and the problems associated with low water levels based on climate analyses.

[1] Formal request from both governments to the International Joint Commission (IJC) to provide recommendations on addressing a specific issue.

2 DECISION SCALING INTEGRATES CLIMATE SCIENCE AND WATER MANAGEMENT

Many 21st century water resources studies use climate models to develop several possible future hydrologic conditions that would affect the impacts in a particular water system. Tests based on this approach are limited to the range of hydrologic inputs created by the climate modeling. In contrast, the strategy described in this document follows a process called "decision scaling". Decision scaling goes beyond making climatological projections, which are inevitably uncertain, to consider how to make robust decisions despite that uncertainty. Decision scaling stress tests the system to see how it would respond to more and more extreme hydrology and then considers the plausibility of the hydrology, the magnitude of the impacts and the mitigation strategies together as the basis for planning. Here, the word "plausible" means there is some evidence that a flood of a certain magnitude could occur based on an analysis or regional data.

For the LCRR study, that evidence will be supplied through work in four perspectives:

1. Stochastically generated future net basin supplies (NBS)
2. Probable Maximum Flood
3. Stress test the system with NBS developed using a "weather generator"
4. Climate modeling

Each of these perspectives is discussed in this report. The four perspectives will be used together to challenge and refine findings from the individual perspectives about likely Lake Champlain levels in the 21st century.

Of the four perspectives, only the stochastic modeling will assign a probability to floods much larger than the flood of record. This sort of planning is facilitated with the use of models like ISEE which show the flood impact building by building, displayed on a map. The decision scaling approach was pioneered by Dr. Casey Brown and is the method used in several peer reviewed journal papers (Brown et al, 2012; Moody & Brown, 2012; Ghile et al, 2014; Steinschneider et al, 2015; Poff et al, 2016). It is also the approach endorsed by the IJC in its climate strategy for the many international Boards it has established. In this study, a traditional climate analysis suggests that flood risk will decline over the 21st century, although any one year could experience a flood greater than 2011. Analysis from each of the four perspectives shows that floods much worse than 2011 are plausible and that flood response planning now, using tools like those developed in this study, is a good response to such high impact, low probability events.

Based on the assessments conducted as part of the LCRR study, it should be noted that the probability of the largest plausible floods in this study will be too small to affect the benefit-cost ratio of a structural project.

However, there may be measures that could be taken only if a flood this large is imminent, and knowing the upper limits of flooding allows flood response planners to consider what those measures would be and where they would need to be applied.

3 EXPERT TEAM

A team of experts will carry out the analysis from the four perspectives. With respect to climate modeling (Perspective 4), a paper titled "Will Evolving Climate Conditions Increase the Risk of Floods of the Large U.S.-Canada Transboundary Richelieu River Basin?" was written by Phillipe Lucas-Picher, Simon Lachance-Cloutier, Richard Arsenault, Annie Poulin, Simon Ricard, Richard Turcotte, and Francois Brissette. Dr. Turcotte is a Board member and Messrs. Lucas-Picher and Lachance-Cloutier are advising the Board on this decision-scaling effort. Dr. Taha Ouarda leads the probable maximum flood effort. Dr. Taesam Lee is producing the stochastic net basin supplies. Dr. Baptiste Francois will generate the stress testing temperature and precipitation inputs that will be entered into the hydrologic basin model to produce stress testing net basin supplies, and Dr. Casey Brown will lead the overall decision-scaling effort that integrates these perspectives. This team will be supported by some LCRR Board members who have extensive experience in addressing climate uncertainty as well as experts on the technical working groups.

4 THE TYPES OF CLIMATE RELATED FINDINGS AND RECOMMENDATIONS THE BOARD COULD MAKE

The LCRR Study Board expects to make a finding about the impact of climate change on future Lake Champlain levels and Richelieu River flows. The main study concern is transboundary flooding, but should this research provide evidence that lake levels will generally decline over the 21st century, the Board could make an associated finding, not just because of a reduction in flood risk, but because of the increased risks of impacts to recreation and the environment.

The Board may recommend alternatives that could reduce future flood risk. The Board has organized alternatives into four themes (Figure 1). Structural measures fall into either Theme 1 (structures such as diversions that reduce water levels resulting from a given set of inflows) or Theme 2 (upland storage to reduce the rate of inflows to Lake Champlain).

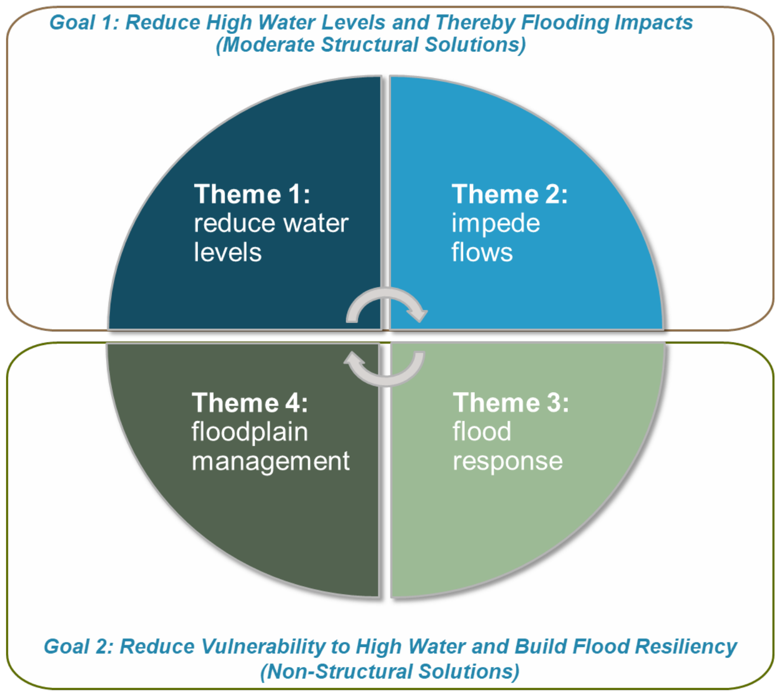

Figure 1. Alternatives to address flooding are organized into four themes.

Theme 1 and 2 alternatives would be assessed in part by a comparison of benefits and costs. The costs to build the structures are near term and, within limits, predictable. But the benefits are largely due to the expected value of reductions in inundation damages; expected value is a combination of the magnitude and probability of an impact. The Board's decisions about Theme 1 and 2 alternatives will thus be premised on estimates of future stage-frequencies.

The Board will also decide whether to recommend best management practices for flood contingency planning measures (Theme 3). The costs for these measures are generally smaller and to some degree expended only when flooding is imminent. A contingency plan is a plan designed to take a possible future event or circumstance into account, so the important consideration for decision scaling is whether or not a flood of a certain magnitude or timing is plausible.

Finally, the Board will consider alternatives for better floodplain management (Theme 4). These alternatives may combine the requirements for the first three themes. Traditionally, floodplain management focuses on the floodplain as delineated by a flood of a certain frequency, and to the degree the Board follows that tradition, it will consider future stage or discharge frequencies. This may also apply to any Board finding or recommendation about flood insurance as a driver for floodplain management. On the other hand, insurance is a tool that can be used to protect against large but unlikely impacts, and the Board may find that land management restrictions or guidelines for property well outside the delineated floodplain may help reduce future damages, so the determination of whether a large flood is plausible (with no reliable estimate of frequency) may also be important.

5 APPLYING FOUR DIFFERENT PERSPECTIVES TO ESTIMATE FUTURE FLOOD LEVELS

The study experts will analyze the impact of climate change on flooding in the study area by estimating the change and variability of net basin supplies (NBS) into Lake Champlain. The Study Board commissioned a study (Lucas-Picher, 2020) that uses climate models to drive a model of the Lake Champlain-Richelieu River basin that forecasts flow into the Lake. In addition, the study experts will stress test the system using NBS developed from three other perspectives. The four perspectives, and the status of each effort at the time this strategy report was written, are:

1. Stochastically generated future NBS datasets
2. Probable Maximum Flood
3. Stress test NBS developed using a "weather generator"
4. Climate modeling (peer reviewed climate research published in 2020)

Each perspective is described below.

5.1 PERSPECTIVE 1. STOCHASTICALLY GENERATED FUTURE NET BASIN SUPPLIES

These evaluations are based on the idea that probability theory can be applied to hydrologic data to determine the odds that floods of different magnitudes will occur in the future. This effort is led by Dr. Taesam Lee. Dr. Lee's team will develop different stochastic net basin supply sets using different assumptions about the patterns in the historic supplies that help predict patterns in future supplies. The supplies can be translated into water levels and flood extent using computer models. Dr. Lee provided three sets of computed stochastic net basin supplies in January 2021, so this strategy report includes an initial review of those results.

Dr. Taesam Lee is a professor of civil engineering at Gyeongsang National University in Jinju, South Korea. He earned his Ph.D. at Colorado State and is the lead author of many peer reviewed papers related to the stochastic analysis of net basin supplies that he is leading for the LCRR Study.

Statistical hydrologists have developed computer models that generate synthetic hydrologic datasets longer than the historic record, thereby generating larger floods than any in the historic record for planning purposes.

These sequences used to be constructed on the assumption that the climate was stationary and the mean and standard deviation should stay the same as the historical mean and standard deviation.

Dr. Lee was asked to assume climate is non-stationary, and he applied three different methods based on three different assumptions:

1 the mean of future NBS will exhibit a steadily increasing or decreasing trend,

2 the mean will shift from time to time, or

3 the mean will vary cyclically.

The three assumptions are illustrated in Figure 2, which contains three graphs of the same historic 1924-2017 NBS, but with the three assumptions described above for the wet and dry periods in the historic record.

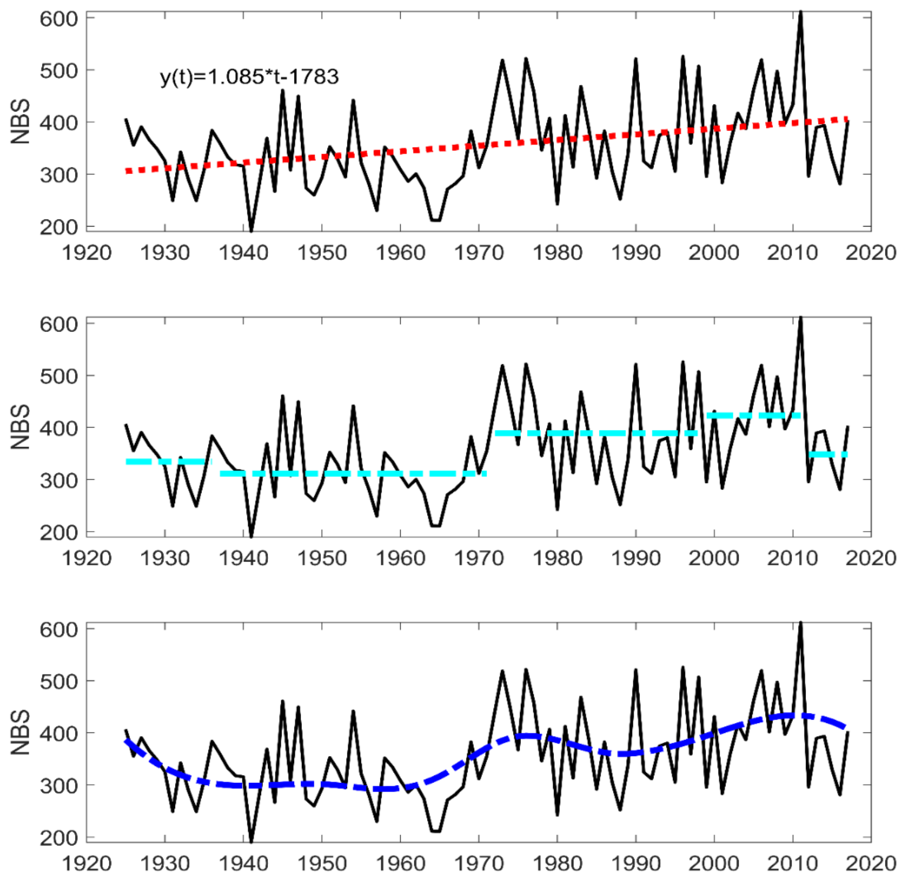

Figure 2. Three characterizations of historical Lake Champlain NBS: trending (top), shifting (middle) and cyclic means.

5.1.1 Trending and shifting mean models.

The trending and shifting mean models are the easiest to understand. If the mean is trending up, this model will produce annual NBS series that tend to be wetter as time progresses. In the shifting mean model, the average annual NBS will move up and down over the 21st century. The shifting mean model was originally used to reflect known and dramatic changes in causation, such as a volcanic eruption, rather than random or unknown processes, but as the middle graph in Figure 2 shows, the shifts in the mean can be inferred from an analysis of historic data; the mean net basin supply shifted up around 1970 and again at the end of the century. But what appear to be simple shifts in a short data record could be part of a more complex set of cycles of wet and dry periods. The bottom graph interprets the same data as the middle graph but with more nuanced results. Some of the mathematical tools for determining the presence of these cycles and their usefulness for predicting the future are described below.

5.1.2 Analyzing cycles in time series data

There are a number of rigorous mathematical methods for characterizing cyclical patterns in data, even if they are hard to see or pin down. Jean-Baptiste Joseph Fourier, a French mathematician at the turn of the 19th century, proved that any dataset can be defined as a series of sine and cosine equations, whose graphs look like wave patterns (sinusoidal). A Fourier analysis will produce cycles, but, depending on the data, the cycles may be too complex to provide any insights into the data or support projections about future data. The Fourier transform is considered a special case of a more general method to analyze data cycles called wavelet analysis.

Wavelet analysis is generally seen as an improvement on Fourier analysis, being more useful for projecting when wet and dry cycles might next occur. Dr. Lee chose to use a third method (Figure 3), empirical mode decomposition (EMD), which is thought to be better than wavelet analysis. EMD uses an algorithm to generate intrinsic mode functions (a cyclic pattern sinusoidal in appearance with specific characteristics concerning the number of peaks and changes between positive and negative).

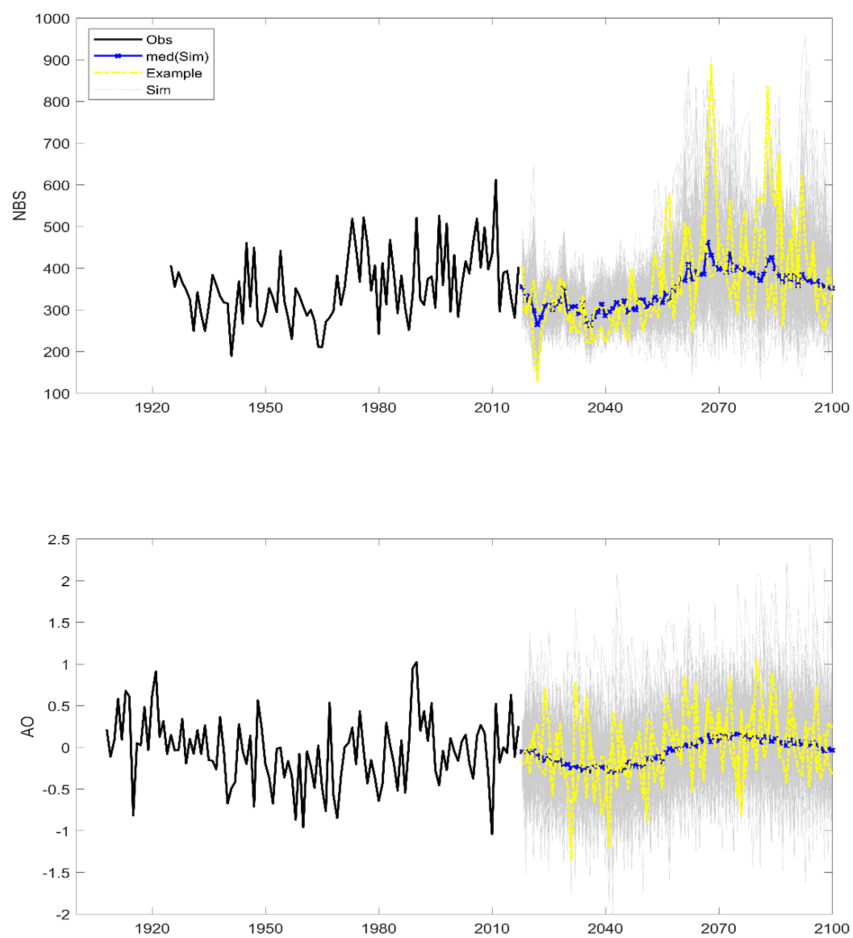

Figure 3. The projected cycle in the Arctic Oscillation (lower figure) drives NBS cycles in the CSHS stochastic NBS simulation (upper figure).

Dr. Lee used a nonstationary oscillation resampling (NSOR) technique to model the EMD components. The results of this third analysis are labeled either as the Climate Signal-led Hydrologic Stochastic simulation model (CSHS) or the EMD-NSOR method based on the Arctic Oscillation (AO) index. The AO index reflects atmospheric pressures around the North Pole, and these pressure changes affect the location of the jet stream, influencing weather in the LCRR basin. A positive AO index is imperfectly correlated with wetter NBS (Figure 4); when the index (the dashed red line in Figure 4) is above zero, net basin supply (solid blue line) tends to be higher than average.

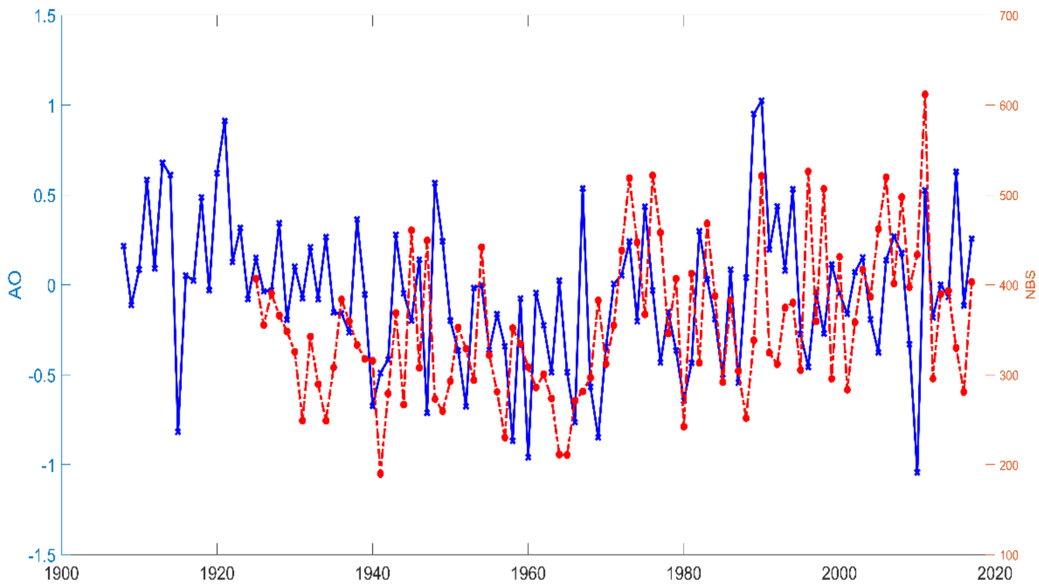

Figure 4. Plot of past AO index values (red dashed graph, left y-axis) and annual NBS (Blue line, right y-axis).

Dr. Lee found that the shifting mean and SML and EMD-NSOR models reproduced the historical drought and surplus statistics as well as the key statistics. He conducted a detailed comparison that indicates that the EMD-NSOR model outperforms the SML model, especially for the long-term variability of the observed NBS shown with the Hurst coefficient (a measure of whether flood years are random or clump one after the other in sequence). The overall results led him to conclude that the EMD-NSOR model would be the best way to simulate the future NBS in the LCRR basin.

Water balance model simulations using the net basin supplies provided by Dr. Lee include some simulations with Lake Champlain elevations of 32.3 meters and more (about 106 feet, (Figure 5) (for reference, the maximum lake elevation during the 2011 flood was 31.32 meters, or 102.77 feet). The SML stochastic NBS results have been used as input to the water balance model, producing five years when lake levels reach 104 feet (31.7 meters), up to a maximum of 104.89 feet (31.97 meters). Results from the EMD-NSOR also include water levels much higher than the 2011 flood. Using preliminary damage numbers for the Hazus[2] study of New York inundation damages, a water level of 104.9 feet would cause thirty times as much damage as a flood of 103 feet (31.4 meters), with more than 220 times as much damage at 106.7 feet (32.5

[2] Hazus is a FEMA hazard estimation software being used on this Lake Champlain study to develop stage-damage tables for U.S. properties. The Hazus outputs will be used in the ISEE model to estimate how U.S. inundation damages would change with changes in net basin supplies or water level changes caused by Theme 1 alternatives.

m). Although these damages are under review now, the concern remains that damages increase in a non-linear way when water levels exceed 103 feet because flood waters engulf areas of development that were thought to be free of flood risk. The study will be processing the trending, shifting and oscillating mean datasets and will report on how they were used to evaluate and rank decisions in the study's Decision Scaling report.

Figure 5. A one-year trace from the AO stochastic NBS datasets with a maximum level of 32.31m. (105.99 feet).

5.2 PERSPECTIVE 2. PROBABLE MAXIMUM FLOOD

Dr. Taha Ouarda leads this effort. The objective of this evaluation is to develop Probable Maximum Flood (PMF) estimates in the Lake Champlain – Richelieu River system. The intent is to determine if there is an outer limit that contains essentially all flood risk, a boundary past which development can occur without risk of being flooded by Lake Champlain. Probable maximum precipitation and flood estimates were used a century ago to size dam spillways. Since the requirement for benefit-cost justifications starting with the Flood Control Act of 1936 in the United States, almost all flood structures are sized to optimize net benefits, which in practical terms means they are unlikely to contain the PMF. Nonetheless, US Principles and Guidelines required the US Army Corps of Engineers (USACE) to estimate the PMF to assure that the optimized project would not cause a catastrophe in the event of a flood greater than the design flood.

> Dr. Taha Ouarda heads the Canada Research Chair in Statistical Hydro-Climatology at INRS-ETE in Quebec City. His specialization is statistical hydrometeorology. He earned his Ph.D. at Colorado State University, world renowned for this type of analysis. He has worked with IJC analyzing trend change points in Great Lakes water levels and has produced stochastic time series for inflows to the Great Lakes or the Richelieu River.

Because these rules applied in so many planning studies, rules were developed to estimate the PMF for USACE, the US Federal Energy Regulatory Commission and the US Bureau of Reclamation.Those agencies did not characterize the PMF in probabilistic terms, and different methods will produce estimates of different sizes. The PMF is useful for planning purposes, but is a theoretical construct that may never occur within realistic planning horizons.

A data-based PMF estimate for this system would be more complicated than the calculation of the probable maximum precipitation (PMP) and runoff used in traditional catastrophic flood calculations. The estimate would have to consider how an extreme storm event would affect the timing of peak flows on the tributaries to the lake, what combination of heavy snowpack and spring temperatures would place the heaviest rain on the greatest water-equivalent snowpack, and then how the onset date and duration of the event would affect the time series of water levels in the lake. The higher Lake Champlain levels rise, the greater the release, so the greater the inflow needed to maintain the same water level. Insufficient data are available to support such an analysis of the joint probabilities of snowfall, January-April temperatures, snowmelt, and spring precipitation. Given this, an alternative approach is being developed to generate the equivalent of a worst-case flood scenario.

5.3 PERSPECTIVE 3. STRESS TEST THE SYSTEM WITH NBS DEVELOPED USING A "WEATHER GENERATOR"

Drs. Casey Brown and Baptiste Francois at the University of Massachusetts are exploring this perspective, identifying how different changes in annual temperature and precipitation would affect flooding, and then considering whether or not those changes are plausible. A so-called "weather generator" will drive the same Hydrotel model used in the Picher climate paper (discussed below in Perspective 4. Climate modeling, page 14), using incremental increases from the current precipitation and temperatures in the basin (annual temperature increases of up to six degrees Celsius and up to a 50 percent increase in annual precipitation). The generator produces time series with year-to-year and within year variations to simulate natural variability around the mean. One hundred seventy-five datasets will be generated for use as precipitation and temperature input datasets for the Hydrotel basin model, which will calculate net basin supply datasets suitable for the water balance model (Figure 6 illustrates the flow of model results from each perspective). This generator series has been run to produce net basin supply datasets, and the NBS datasets are being used as inputs to the water balance model to produce lake level and release time series.

Dr. Casey Brown is a Professor in the Department of Civil and Environmental Engineering at the University of Massachusetts, Amherst. He earned his Ph.D. at Harvard in 2004. He has worked with the NSF, Rockefeller Foundation, and World Bank and is internationally recognized for his decision scaling approach towards using climate science in the service of water management decisions.

Dr. Baptiste Francois is an Assistant Professor in the Department of Civil and Environmental Engineering at the University of Massachusetts, Amherst. He earned his Ph.D. at University of Grenoble-Alpes, Grenoble (France) in 2013 on the optimal management of multi-purpose reservoir and climate change.

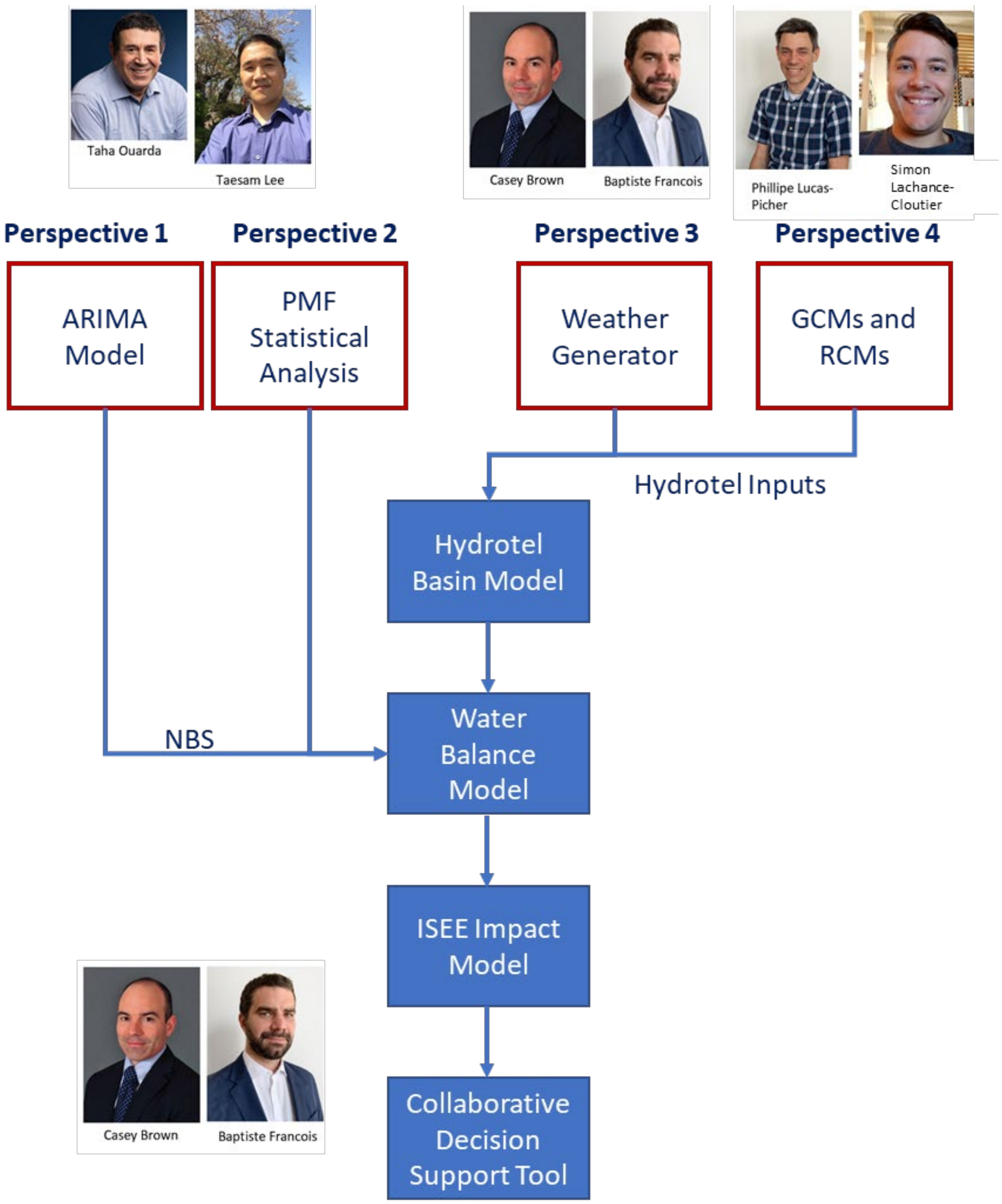

Figure 6. Three climate expert teams will provide input to the Hydrotel basin model to support quantitative evaluations of climate related flood risks.

Figure 7, Figure 8 and Figure 9 show how the foundation for the plausibility of higher than 2011 floods is being established by both the weather generator (Perspective 3) and the climate research (Perspective 4). Figure 7 is a graph of the net basin supplies in one climate simulation; it was chosen because it shows that the weather generator model results demonstrate the plausibility of much higher than 2011 net basin supplies. Figure 8 shows the water levels produced when those net basin supplies are run through the water balance model. Figure 9 shows the maximum daily NBS produced by the Hydrotel simulations driven by the weather generator. It is displayed there, alongside one NBS series and water balance simulations from the climate study that produced a peak Lake Champlain level of 107.72 feet (32.83 m). Although the units are not exactly comparable, the weather generator NBS results suggest that water levels of over 107 feet (32.6 m) could be possible with as little as a 20% increase in average annual precipitation.

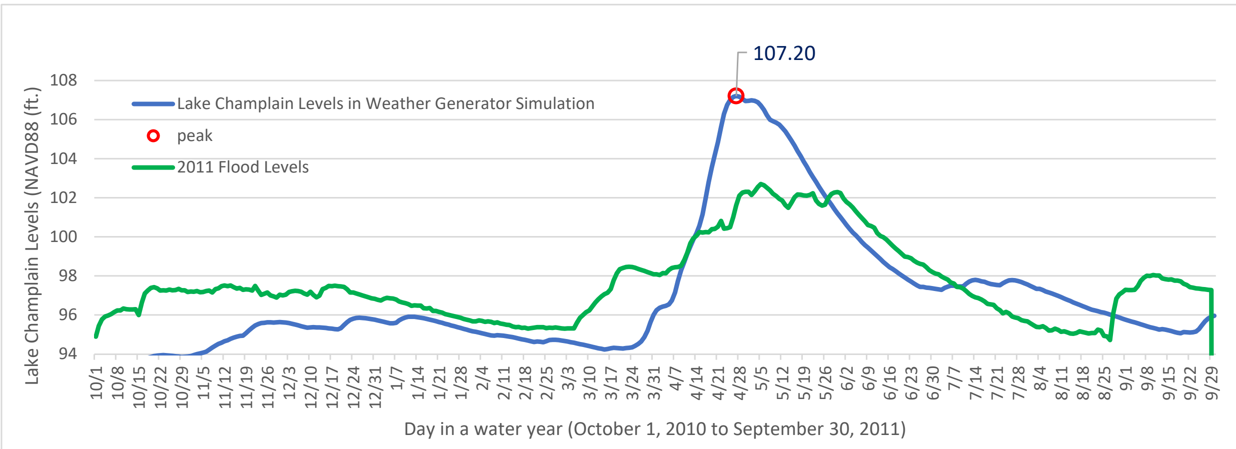

Figure 7. Net basin supply rates from one climate model projection.

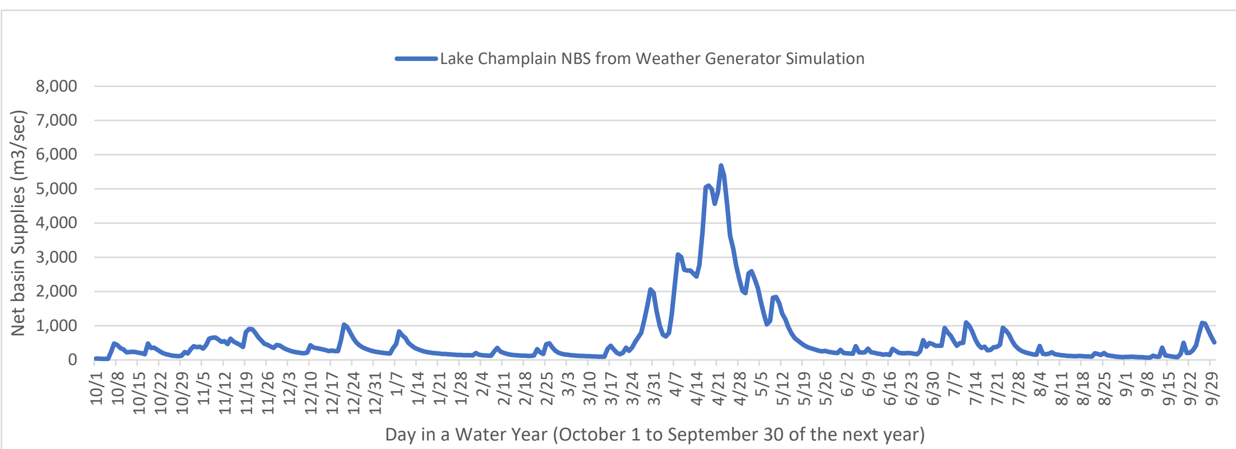

Figure 8. Water balance estimates for Lake Champlain levels based on the NBS sequence in Figure 7.

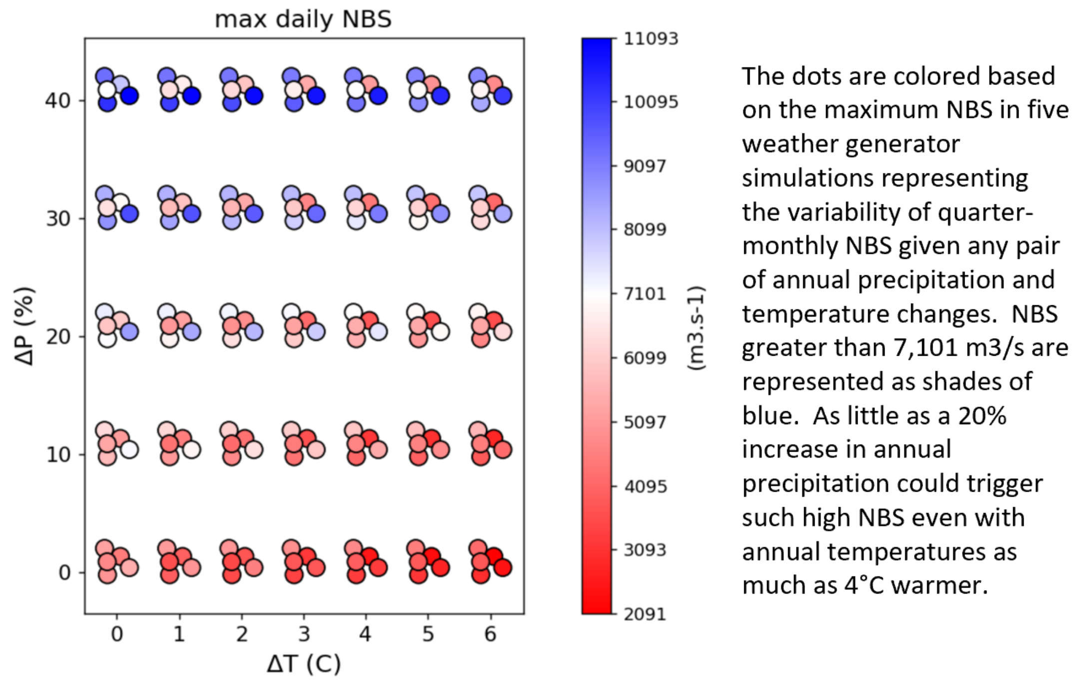

Figure 9. Maximum daily NBS for weather generator simulations at different temperature and precipitation changes.

Lake Champlain levels are a function of antecedent levels and net basin supplies. If the lake is low, it can accommodate record high inflows without flooding. If the lake is high, any net basin supplies greater than the outflow capacity will cause the lake to flood. The water balance model used in this study includes a quarter-monthly average net basin supply of 2,235 m^3/s in 2011, less than the 2,626 m^3/s for March 1936, when the lake was lower, and this large inflow did not cause the lake to rise to 2011 levels. Maximum daily net basin supplies would be higher than quarter-monthly averages. In 2011, the peak daily NBS was 3,234 m^3/s. For comparison purposes, the 2011 peak would fall near the lower end of the NBS scale shown in Figure 9.

5.4 PERSPECTIVE 4. CLIMATE MODELING

The climate modeling team is led by Philippe Lucas-Picher. Philippe Lucas-Picher, Simon Lachance-Cloutier, Richard Arsenault, Annie Poulin, Simon Ricard, Richard Turcotte, and Francois Brissette published a peer-reviewed paper (Lucas-Picher et al, 2020) asking, "Will Evolving Climate Conditions Increase the Risk of Floods of the Large U.S.-Canada Transboundary Richelieu River Basin?" The research conducted to develop the paper involved using three bias-corrected multi-resolution ensembles of climate projections for two greenhouse gas concentration scenarios as inputs to drive Hydrotel (a state-of-the-art, high-resolution, distributed hydrological model). The paper predicts a downward trend in the mean annual net basin supplies to Lake Champlain. In most simulations, the increase in annual evapotranspiration, caused by higher temperature, is greater that the relatively modest increase in annual precipitation projected by most climate models.

Dr. Phillipe Lucas-Picher is a climate scientist at the Swedish Meteorological and Hydrological Institute. He was educated at the University of Quebec in Montreal, earning his Ph.D. in Environmental Science in 2008 and a masters in Atmospheric Science in 2003. He has written extensively about the practice of estimating future hydrology from global and regional climate models.

The paper also concludes that the probability of flooding will be less in future climate conditions, despite the fact that most climate models show a roughly 0 to 30 percent increase in average winter and spring precipitation. For example, the 20-year return period flood flow (a medium sized flood that causes little damage now) should decrease between 8 percent and 35 percent for the end of the 21st Century (2070–2099) time horizon and for the high-emission scenario representative concentration pathway (RCP 8.5). The physical explanations for this reduction in flood risks are decreased snow accumulations and an increase in evapotranspiration, both a product of the higher temperatures expected in the region.

The estimates of future evaporation weighed heavily in this conclusion, and became an issue for discussion among the expert team (see the discussion starting on page 17.)

The authors recommended that the region remain vigilant because the year-to-year variability of flooding could still produce a major flood even as the average lake levels declined. Even though this is a flood study, the Board might also wish to consider informing regional governments that the future could bring much lower lake levels, affecting boating and harmful algal blooms.

5.5 COLLABORATION AND COORDINATION

Among the Three Teams The three expert teams will provide either net basin supplies as input to the water balance model to produce Lake Champlain levels and releases, or inputs to the Hydrotel model using in the climate study, in which case the Hydrotel model will produce the NBS datasets to produce levels and flows (Figure 6).

The flowchart of tasks from all teams, including the outputs of one team that inform another team are shown in Figure 10. The major reports from this work are shown in Figure 11.

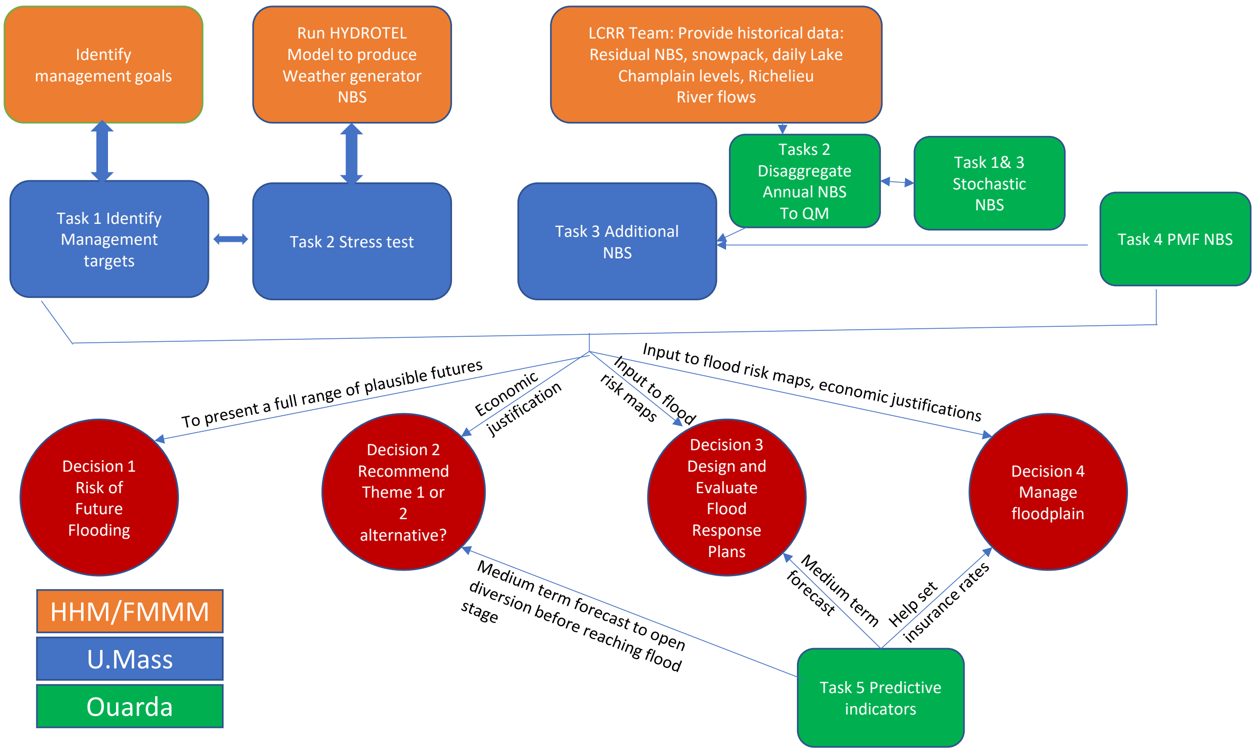

Figure 10. A flowchart showing how the tasks of each team contribute to the decision scaling effort.

Figure 11. Reports from LCRR Decision Scaling Work.

5.6 PEER DISCUSSIONS

Any attempt to project climate conditions and the future likelihood of flooding will be filled with questions. Journal articles on a research course are peer reviewed to help identify issues that could undermine the findings of a paper, but that review is done late in the research process by people not familiar with the research and with limited time and access to the research team. In this work, the experts have agreed to identify key uncertainties, issues, and doubt in this research, develop some estimate of which of these will have the greatest influence on shaping the Board's findings and recommendations, discuss what should be done to address the uncertainty, and then record that resolution as part of the Decision Scaling final report. The hope is that the discussion of these uncertainties will make the analysis more robust and provide additional value to others engaged in similar work.

Seven key issues have already been identified as the strategy was being developed. A preliminary discussion of the second issue (evapotranspiration) is included to illustrate how these discussions will be captured.

1. The relevance of different representative concentration pathways (RCPs) to the issue of future flooding in this basin.

2. Evapotranspiration estimates in the Hydrotel model.

3. A reflection on what the bias correction shows us about uncertainties in modeling climate effects on net basin supplies.

4. Potential exaggerations of flood risk from the design of a probable maximum lake flood.

5. Potential misrepresentations of flood risk from transferring information from nearby basins (e.g., 2017 and 2019 in Ottawa River).

6. The influence of longer term quasi-periodic cycles in long term trends and the potential value of teleconnections for understanding those trends and predicting cycle inflection points.

7. Extracting the precipitation and temperature patterns from the four perspectives to offer tangible notions of the types of weather that could cause megafloods.

An example of documenting internal peer discussions: evapotranspiration estimates in the Hydrotel model.

This was one of the first issues raised among the climate change experts on the study. A preliminary discussion for this one issue is included here to illustrate the form these discussions will take.

5.7 THE ISSUE

Questions were raised about whether the downward trend projected for NBS was driven by an overestimate of evaporation. On the Great Lakes, for example, climatologists now believe that the increase in precipitation will more than overcome the increase in evaporation and lake levels will trend upward. But evaporation from the Great Lakes is more of an issue than evaporation from Lake Champlain because the lake surface is only about 5 percent of the drainage area compared to about 47 percent for the Great Lakes. In the Lake Champlain basin, the issue is evapotranspiration, defined as "the process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants."

5.8 THE RELEVANT FACTS

Hydrotel calculates the potential evapotranspiration (PET) as a function of temperature and a calibrated coefficient, and then calculates the actual evapotranspiration (ET) as limited by soil moisture and physical characteristics affecting the movement of water from land to air. One hundred seventy-five sets of Hydrotel input data from the weather generator being used by Casey Brown and Baptiste Francois to characterize a wide array of future climate conditions can also be used to produce the combined effects of precipitation and temperature on actual evapotranspiration (ET) as calculated by Hydrotel. The basin already has all the water it needs to supply evapotranspiration, so the PET has to increase (in this case by warming) if ET is to increase. The results show that annual ET will increase by 42 mm for every 1°C increase in temperature. Said another way, if annual temperatures increase 1°C, precipitation would have to increase by 4 percent to keep annual inflows the same.

Ideally, we would test the validity of the model by comparing modeled to actual evapotranspiration, but there are no large-scale direct measurements for the Richelieu River. There are two datasets, one in southern Quebec and the other a northeast portion of a US dataset, which can be used to deduce what evapotranspiration must have been, assuming ET is the residual when the precipitation and runoff components have been identified.

A water balance model tracks where the water goes. In a rainy period, ET will be minimized, and the volume of water stored in the soil will increase, and in a warm sunny period, ET will be much greater than precipitation (P) because it can draw from water stored in the soil. Over a long period of time water that falls onto land will either run off (R) into streams or go back into the air through evaporation, so $ET=P-R+\Delta S$ becomes $ET = P-R$ because long term, the amount of water stored in the soil stays about the same; ΔS is zero.

Using that concept, data on P and R from 29 Quebec watersheds physically similar to the Richelieu River were used to calculate ET. Over these 29 watersheds, there was a range of temperatures, so the 29 ETs could be correlated with the 29 average annual temperatures. The slope of that correlation is 40 mm/°C. This slope is close to the value (42) determined from the weather generator simulations, providing evidence (but does not prove) that the Hydrotel model ET estimates are valid. Other factors that may affect ET vary between warmer and cooler basins. And although they are near the Richelieu River, these basins have a mean temperature lower than that of the LCRR basin and have a lower ET/P ratio.

The other dataset from the northeast United States is extracted from a US-wide dataset used in a USGS study looking at, among other things, annual evapotranspiration rates. Using the water balance approach, the relationship between increasing temperatures and evapotranspiration is again mostly linear, suggesting temperature is the driving factor, but the rate is lower, at 30.2 mm/°C. At worst – assuming these data are better suited to represent the LCRR basin - this suggests that the Hydrotel evapotranspiration function is of the right form, but the coefficient is too high by one-third.

How important is the estimate of evapotranspiration to the sound estimation of flooding in LCRR? It has been well established that annual net basin supplies have been increasing, causing a noticeable increase in average annual Lake Champlain levels, but without an accompanying rise in flooding. This is because precipitation has increased outside of April and May, when over 80 percent of peak flooding has historically occurred. Annual NBS does not correlate well with flooding, but the so called NBS14d (the maximum fourteen-day NBS each year) does. Warmer temperatures mean less snowpack and more ET in April and May. Could these counter-flood trends be explained by using a new set of Weather Generator inputs to the Hydrotel model?

Baptiste Francois prepared 35 additional weather generator input series in which temperature increases applied only to November, December, January, February, March and April, (six month warming) thereby simulating the impacts of warmer weather just on snowpack and ET leading up to the flood season.

This experiment produced two distinct findings:

- The first finding is about temperature and ET. NBS14d is reduced as temperature increases in both the whole year and six-month weather generator inputs. Holding precipitation constant, the impact is about 20 percent at 2°C warming for both six and twelve month warming, but at 3°C, year round warming reduced NBS14d more than six month warming. Does this suggest that increasing ET means reduced flooding? The six and twelve-month warming scenarios should have had similar impacts on snowpack, so why do warmer temperatures May through October reduce flooding? Is it because of ET in May? There is little over-year impact on next year flooding.

- The second finding is about temperature and snowpack. The warming of winter temperatures will probably have the impact of reducing the NBS14d quite significantly with a drop of about 15 percent for a warming of 1°C and about 20 percent for a warming of 2°C because of reduced snowpack.

5.9 EXAMPLE RESOLUTION

This evaluation does not prove that climate change will reduce the threat from flooding, but it does show that conclusion cannot be dismissed because the model's estimate of ET creates a biased perspective.

6 SIMULATION OF DAMAGES FROM DECISION SCALING NET BASIN SUPPLIES

Decision scaling maps climate science to the specific requirements of different decisions. As discussed in Categorical findings and recommendations (page 22), most of the costs of Theme 1 and 2 alternatives are expended before the investments can produce benefits. These near present costs are weighed against future uncertain benefits using expected damages (damage amount times the probability of the damage occurring). Medium size floods tend to be the most influential because the probability factor is relatively large. The Board could also consider small investments in flood response plans (Theme 3) to protect against catastrophic damages from plausible floods with probabilities too small to estimate with any confidence. In this case, the expected value of the benefits is highly uncertain, and many of the costs will only be required if there is a large flood, so the main use of climate information in Theme 3 decisions may be to establish the plausibility, not the probability of large floods.

In between these two, the Board must consider floodplain management (Theme 4), which can change the vulnerability to flooding over time, but with results driven by the sequence of future floods. Floodplains have typically been delineated by “100 year” or similar recurrence intervals, with special treatment of property within that specific delineation. FEMA plans to implement Risk Rating 2.0 this year, with a more nuanced view of risk within and outside the 100-year delineation, so it is not clear how the Board might consider the use of climate change informed flood frequency calculations to regulate development.

7 ASSESSING PLANS FROM FOUR PERSPECTIVES

Strengths and weaknesses of the four perspectives

Each perspective has strengths and weaknesses; each adds to the information provided by all the others. The perspectives can be mixed specifically for decisions related to each Theme. Table 1 summarizes the primary strengths and weaknesses of using each approach alone to estimate and manage flood risk. At this time, there are some apparent differences in the projections according to the perspective which will have to explained or refined. Climate modeling results show a declining trend in the annual average net basin supplies. The Arctic Oscillation driven stochastic time series shows the worst floods occurring later in the 21st century while the average NBS is stable over the century. This may be because the climate study explicitly factors in the impact of temperature on evapotranspiration, while the AO stochastic NBS is influenced by temperature only insofar as it was an implicit factor in historic AO-NBS correlations.

Table 1. Strengths and weaknesses of each perspective.

Strengths	Weaknesses
1. Stochastic	
Projections of NBS from past NBS eliminates the need to theorize how climate change affects net basin supplies and the resultant uncertainty introduced by that step.	NBS projections are based on patterns which may change in the future. Meaningful estimates of the probability of extreme floods are less defensible than estimate of more common floods because of limited data and the difficulty of validating the fit of distributions to extreme events. NBS projections are made, but not precipitation or temperature projections which could be used to characterize the weather patterns leading to megafloods.
2. PMF	
Focuses on the interaction of the most damaging snowpack, spring temperatures and spring precipitation. The interaction of these three semi-independent phenomena created the 2011 flood. Helps set a reasonable geographic boundary for flood response and floodplain management.	An estimate of the probable maximum lake level is more complicated than an estimate of the probable maximum river stage because it is dependent not just on the magnitude of weather events, but the sequential timing of each of the three components and the antecedent lake levels for each timestep in the sequence. The concept of PMFs is contested based on the qualitative nature of methods used and lack of reproducibility of those methods.
3. Stress Testing	
Provides a range of NBS that goes beyond climate model predictions by considering the impact of large precipitation and temperature changes that could happen. The broader range can help define inflection points in the impacts useful for planning. Associates specific combinations of temperature and precipitation with flooding, which can help provide an intuition about the likelihood of occurrence.	Biases in the statistical model are possible and will influence the variability in each trace.
4. Use of RCM and GCM	
The only approach that evaluates the impact changes in the earth energy balance will have on LCRR hydrology. Large ensemble of RCM and GCM simulations are available. Use of GCM and RCM is a rational, well accepted approach followed by the International Panel on Climate Change.	Despite their usefulness, GCM and RCM driven models are subject to limitations (lack of resolution, missing physical processes etc.) that might produce a bias in the simulation of outputs. The magnitude of the bias and necessity of correction procedures reveal how difficult it is to predict future runoff. Only one hydrological model was used. The ensemble of climate models chosen may or may not fairly represent the range of equally plausible futures.

8 CATEGORICAL FINDINGS AND RECOMMENDATIONS

The Study Board will develop findings on the future vulnerability of the basin to flood damage and will make recommendations to use different kinds of flood management approaches. The intent of this climate strategy is not to offer one "correct" estimate of future net basin supplies, an unattainable goal, but to provide the appropriate array of net basin supply scenarios to test the robustness of Board recommendations. The following text explains the NBS framework that will be used to test Theme 1 and 2 solutions, and the very different frameworks for Theme 3 and Theme 4 alternatives.

8.1 GENERAL FINDINGS ON THE EFFECT OF CLIMATE CHANGE ON FUTURE LAKE CHAMPLAIN LEVELS AND RICHELIEU RIVER FLOWS

The partial results already available from the four perspectives do not establish a clear picture of how climate change will affect Lake Champlain levels and Richelieu River flows in the remainder of the 21st century. The authors of the JAWRA paper find that climate model driven simulations show that average annual net basin supplies will decline over that period, but they warn that significant floods could still occur, a product of the variability of the supplies. The stochastic simulations based on the Arctic Oscillation Index show the highest lake levels occurring later in the century. Results from all four perspectives offer clear evidence of the plausibility of megafloods much higher than the 2011 event.

Even if there is some refinement in these findings, it is likely that the Board will find that the effect of climate on future flood levels is uncertain. In making recommendations, the Board will likely support alternatives that are robust, that is, that will stand as good decisions under a range of future climate impacts. The basis for robust decision making is outlined in the following sections.

8.2 CLIMATE AND THEME 1 AND THEME 2 ALTERNATIVES

Theme 1 alternatives lower flood levels by regulating the flow of water out of Lake Champlain by modifying the Richelieu River channel. Theme 2 alternatives lower flood levels by regulating the flow of water in Lake Champlain by creating pockets of storage along the banks of tributaries to the Lake. Alternatives from both themes require investments and construction before floods happen. If the future holds more frequent and severe floods, the pre-flood investments are more likely to be judged well. If future floods never approach the magnitude of the 2011 flood, then these alternatives are more likely to be considered a waste of money. This may apply most strongly to Theme 1 alternatives, which generally must be completed before they are effective. It is less true of Theme 2 projects because the LCRR study (Rousseau et al, 2021) suggests that the projects are unlikely to be cost-efficient at the basin scale regardless of study climate projections. The LCRR study examined the effectiveness of upstream storage (Theme 2) to reduce Lake Champlain flooding. Four alternatives were considered. The first, using farmland along the tributary banks, would require land almost twice the size of Lake Champlain to reduce a flood the size of 2011 by five centimeters. Three alternatives that restored wetlands would require from one-half to 120 percent the size of Lake Champlain and would reduce the 2011 lake levels from 6 to 12 cm (Rousseau, Savary, & Bazinet, 2021).

In general, Theme 1 and 2 flood management alternatives will not be effective at addressing plausible but unlikely failures because the costs are high and immediate, while the expected benefits are small, diminished by low probabilities. Nonetheless, study experts have now identified Theme 1 alternatives that provide some flood relief for a fraction of the costs of previously designed alternatives, and preliminary benefit-cost analysis suggests that the Crump Weir alternative will have a convincingly strong benefit-cost ratio based on the current climate .[3] The Crump Weir can also raise the lowest water levels and has minimal environmental and social impacts, with no lasting effect on downstream flows. It can also be considered as mitigation for the water level increase caused by the widening of the Chambly Canal. This alternative has been well received by Canadian and Quebec agencies. Decision scaling will be used to determine the robustness of the recommendation to build the weir, and the fact that it provides benefits whether flood risk increases or decreases will give it an advantage over previous Theme 1 alternatives.

8.3 CLIMATE AND THEME 3 AND THEME 4 ALTERNATIVES

Theme 3 alternatives are emergency response plans that temporarily reduce flood vulnerability, developed now but implemented in the future just before a flood is about to happen. Theme 4 alternatives regulate or influence development in the floodplain to reduce unsustainable uses.

In general, Theme 3 alternatives are best for addressing plausible but unlikely failures because the costs of preparing are small and the costs of implementing the response plan are borne only when the failure is imminent. Theme 4 alternatives may be good for addressing plausible but unlikely failures because some Theme 4 measures, like relocations, can also eliminate more common damages. But restricting the use of land to avoid plausible but unlikely flood damage has a similar imbalance as Theme 1 alternatives in that there will be upfront costs and continuing opportunity costs borne even if the flood never happens.

The strategy draws on the experience of our experts in dealing with risk, uncertainty and decision making to pronounce decision postulates that can be tested quantitatively:

- Hedge large, plausible but unlikely risks with financial instruments such as insurance or catastrophe bonds that pay out to the government at different flood levels.
- Large, near term expenditures for Theme 1 projects should be tested with expected values but also scenario analysis to determine the future conditions that could cause regret concerning the decision.

[3] The Crump Weir has not been fully evaluated as this report goes to press. Preliminary evaluations show a benefit-cost ratio of two or three with historic hydrology and a plausible range of discount rates. If future climates produce more and larger floods, the benefit-cost ratio will increase, with larger benefits and the same costs. Much drier climates might would reduce the benefits of the weir; the decision scaling team will investigate whether it is plausible to think the ratio could drop below one. However, the weir raises the lowest water levels, which could create substantial benefits for water quality and recreation, suggesting that building the weir is a robust decision.

- Determining the recurrence interval for the 2011 flood would be important if the question is whether or not to build a Theme 1 solution, but it is not important in developing Theme 3 flood response. The benefit-cost test for structural projects compares near term costs to long term reductions in expected damages, and that requires the determination of the frequency of different size floods. Floodplain regulation since the 1976 floods has greatly reduced the damage that would be caused by floods the size of the 1976 or 1998 floods. Damages in the United States portion of the study area start at about a meter higher than they did in 1976, and most of the buildings damaged in Quebec were built before 1976. As a result, there is not much damage from floods of less than 100-year recurrence intervals, and consequently, the damage reduction potential from structural projects is small in any but the rarest floods.

- Recurrence intervals are relevant to Theme 4 alternatives such as floodplain management and flood insurance but there should not be a quantum change in management at the 100 year or 200-year delineation.

- Because the four perspectives on climate all support the plausibility of low probability floods much greater than 2011, supplement protection provided by the Crump Weir with the use of flood contingency response plans (Theme 3) to reduce the impacts of megafloods if they occur.

9 ADAPTIVE MANAGEMENT

The decision-scaling team will formulate a recommendation on adaptive management after reviewing all the studies and the evaluations of alternatives. In general, adaptive management is a structured process that identifies factors that are both uncertain and important in a planning decision, monitors data after a decision is made to reduce those uncertainties, and if necessary, revisits the decision with improved understanding. At this point, there are several issues that appear to be uncertain and important enough to consider managing them adaptively. The decision scaling team will make recommendations about what and how to monitor these factors at the study conclusion late in 2021. Below are three issues that serve as examples of what might be monitored in an attempt to refine the projections from this study.

9.1 FLOODING AGGRAVATED BY SNOWMELT

The 2011 flood was an example of how Lake Champlain levels can be driven up by the addition of melting snow and heavy spring precipitation. An increase in average annual global temperatures would not necessarily require uniformly higher temperatures between January and April in the Lake Champlain basin, so it is not clear what the contribution of melting snowpack will be in the future.

9.2 EVAPOTRANSPIRATION

The JAWRA paper posits that temperature increases will increase evapotranspiration enough to more than overcome increases in precipitation, causing a decline in net basin supplies and flood risk over time. The reduction in flood risk would be balanced, and perhaps outweighed by the negative impacts of low water levels, which would be more frequent and would affect more people. The decision scaling team will consider whether and how evapotranspiration in the basin could be monitored and correlated with temperature and will consider what governments might do as data help reduce uncertainty about this issue.

9.3 MEGAFLOODS

Water levels much higher than those experienced in 2011 are seen in simulations based on all three stochastic methods, from the weather generator and climate studies, and presumably, the PMF analysis. Damages increase non-linearly in floods above the 100-year flood level as water reaches buildings outside the delineated floodplain. The confluence of snowpack, spring rainfall and January to May temperatures are the factors that create Lake Champlain floods. The simulations of lake levels above 2011 levels suggest that high water levels in April and May are not necessarily preceded by unusually high water levels in January and February (turn to Figure 8, page 12 for example). The study experts hope to investigate Theme 3 alternatives that could reduce damages from megafloods, but at this time, there are no such plans. The Board will have to consider whether to recommend investments against what are in any case unlikely events. Some of that analysis will be done with governments during the final months of this study, but at the end of the LCRR study, there may still be substantial uncertainty about whether the likelihood of such large floods is enough to warrant significant investment in these efforts.

During this study, the decision scaling team will try to characterize the snowpack, spring rainfall and January to May temperature profiles necessary to create these large floods, will consider the individual and joint probabilities of those three conditions, and will assess how the odds of a large flood can be estimated conditionally through the beginning of the year, as the water-equivalent snow volume accumulates and persists, as the pattern of winter to spring temperatures maintains the snowpack, and as spring rains begin. The guiding question will be: how extreme would each of these three factors have to be to produce Lake Champlain levels of 104, 105, 106 or 107 feet?

To the extent that the foundation for that analysis can be laid during this study, it may be advisable to monitor weather statistics for the purpose of at least bracketing the probability of these floods. For example, the greatest one-day precipitation in Burlington, VT, is only 4.19 inches, on October 6, 1932. In Buffalo, NY, the record is 5 inches, for Alabama, 32.52". Are the sorts of rainfall rates and persistence needed for a megaflood uncharacteristic of the climate of this portion of the continent? Will climate change affect that? It may be possible to devise a monitoring plan that looks for climate change related trends that make megafloods seem more likely, and more worthy of investments to reduce megaflood damages.

REFERENCES

Brown, C., Ghile, Y., Laverty, M., and Li, K. (2012). Decision scaling: Linking bottom-up vulnerability analysis with climate projections in the water sector, Water Resour. Res., 48, W09537, https://doi.org/10.1029/2011WR011212.

Ghile, Y.B., Taner, M.Ü., Brown, C. et al. (2014). Bottom-up climate risk assessment of infrastructure investment in the Niger River Basin. Climatic Change, 122, 97–110, https://doi.org/10.1007/s10584-013-1008-9.

Lee, T., & Ouarda, T. (2020). Stochastic Simulation of Annual Net Basin Supply series for the Lake Champlain Richelieu River System. Montreal, QC: IJC LCRR Study.

Lucas-Picher, Philippe; Ricard, Simon; Arsenault, Richard; Lachance-Cloutier, Simon; Poulin, Annie; Brissette, François. (2020). Will Evolving Climate Conditions Increase the Risk of Floods of the Large U.S.-Canada Transboundary Richelieu River Basin? JAWRA Journal of the American Water Resources Association, 57, https://doi.org/10.1111/1752-1688.12891.

Moody, P., and Brown, C. (2012). Modeling stakeholder-defined climate risk on the Upper Great Lakes, Water Resour. Res., 48, W10524, https://doi.org/10.1029/2012WR012497.

Poff, N., Brown, C., Grantham, T. et al. (2016). Sustainable water management under future uncertainty with eco-engineering decision scaling. Nature Clim Change 6, 25–34, https://doi.org/10.1038/nclimate2765.

Rousseau, A. N., Savary, S., & Bazinet, M.-L. (2021). Flood water storage using active and passive approaches. ILCRR Study, IJC.

Steinschneider, Scott; McCrary, Rachel; Wi, Sungwook; Mulligan, Kevin; Mearns, Linda; Brown, Casey. (2015). Expanded Decision-Scaling Framework to Select Robust Long-Term Water-System Plans under Hydroclimatic Uncertainties. Journal of Water Resources Planning and Management, 141 (11):04015023. doi: 10.1061/(ASCE)WR.1943-5452.0000536.

INTERNATIONAL JOINT COMMISSION • COMMISSION MIXTE INTERNATIONALE

1909