Flood Water Storage using Active and Passive Approaches-

Assessing Flood Control Attributes of Wetlands and Riparian Agricultural Land in the Lake Champlain-Richelieu River Watershed

A Report to the International Lake Champlain - Richelieu River Study Board

Submitted by

Alain N. Rousseau P.Eng., Ph.D.

Stéphane Savary Jr.Eng. (EIT), M.Sc.

Marie-Laurence Bazinet

Centre Eau Terre et Environnement

Institut national de la recherche scientifique (INRS-ETE)

490, rue de la Couronne, Québec (QC), G1K 9A9

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TECHNICAL WORKING GROUPS

FMMM, Canada

Ted Yuzik

Syed Moin

Jan Adamowski

Pascal Marceau

FMMM, United States

Bill Werick

Ben Rose

Michael Kline

Matthew Cosby

RR, Canada

Alain Rousseau

Mathieu Roy

Marianne Bachand

Marc Mingelbier

Marie-France Julien

Bernard Doyon

RR, United States

Rose Paul

Phil von Bargen

Timothy Mihuc

Donna Parrish

HHM, 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

Record-setting floods in the Lake Champlain-Richelieu River (LCRR) basin in 2011 prompted the U.S. and Canadian governments to work together to identify how flood forecasting, preparedness and mitigation could be improved in the LCRR basin. As the basin is a transboundary basin, addressing flood risk will require a binational approach. It is therefore in both countries' interests to identify and implement effective solutions to address the flooding issues that are commensurate with each nation's respective risks. The governments of the United States and Canada issued a reference to the International Joint Commission (IJC) pursuant to Article IX of the Boundary Waters Treaty in September of 2016 to complete the 2013 Plan of Study to explore the causes, impacts, risks and solutions to flooding in the LCRR basin. The Commission subsequently formed the International Lake Champlain – Richelieu River Study Board to assist the Commission in responding to the reference.

STUDY FOCUS

The International Lake Champlain – Richelieu River Study (Study) is intended to build upon past studies of flooding mitigation and management options to develop tools that will allow Canadian and US officials and managers to more fully prepare for and manage future floods. The geographical scope of the area addressed in this study is the entire LCRR basin with the downstream limit controlled by the influences of the Saint Lawrence River regime. Study tasks focus primarily on the Lake and River and their adjoining shorelines and flood areas, and include assessment of both structural and non-structural measures to reduce high water levels and associated flooding impacts, reduce vulnerability to high water and build flood resiliency.

INVESTIGATION OF PASSIVE AND ACTIVE APPROACHES TO FLOOD MITIGATION

This report describes an investigation of the effect of passive and active approaches to flood mitigation in the LCRR basin. Specifically, this investigation assessed the potential of: (i) storing flood water on riparian agricultural landscapes and (ii) using current, restored, and constructed wetlands of tributaries in the Vermont and New York subwatersheds to reduce runoff volumes, peak flows and net basin supplies to Lake Champlain.

The assessment focused on four basic questions:

1. Why should we study upland storage?
2. What is the role of wetlands on net basin supply (NBS), flows, and water levels in LCRR?
3. What would be the additional benefit of flooding farmlands? and
4. What would be the effect of additional wetlands?

The answer to the first question is rooted in studies and events that occurred in the Lake Champlain watershed and illustrated the impact of upland storage as a nature-based approach for flood mitigation. The other three questions were answered using the PHYSITEL/HYDROTEL hydrological modelling platform to assess the role of wetlands on inflows to Lake Champlain (i.e., NBS) and flows in the Richelieu River, as well as the additional benefit of flooding farmlands and adding wetlands to mitigate floods.

The PHYSITEL/HYDROTEL hydrological modelling platform is designed to discretize a watershed into river segments and hillslopes, simulate the effect of land cover on flows, and provide input to a lake/reservoir water balance model or a hydraulic or hydrodynamic model to predict lake or river water levels. For this study, the model was calibrated and validated with an extensive database, namely 25 hydrometric stations and 64 years of gridded meteorological data.

The methodological framework was based on turning on and off the wetland parameterization schemes provided by HYDROTEL to single out the flow regulation effect provided by the current distribution of wetlands in the basin and quantify the effect of four basic watershed (a.k.a. upland) storage scenarios:

1. conversion of agricultural land to wetlands within a 1,000-m buffer zone along the entire river network of the LCRR basin using the isolated and riparian wetland modules of HYDROTEL (cumulative area of 2,471 km^2 within the Richelieu River (at Fryers) and 2,256 km^2 for the Lake Champlain basins);

2. converting local topographical depressions into wetlands with different design criteria, e.g., threshold for storage capacity, wetland area and drainage area excluding actual wetlands, water, urban area and roads;

3. addition of wetland areas on land having the potential of naturally accumulating water due to topography and given poorly or very poorly drained soils using a dataset produced by the USEPA to support research and online mapping activities related to the EnviroAtlas; and

4. combining scenarios 2 & 3.

RESULTS & FINDINGS

The simulation results were analyzed in terms of NBS (inflows from all subwatersheds and hillslopes discharging into Lake Champlain, as well as precipitation and evaporation); flows (annual and seasonal high and 7-day low flows) and water levels in Lake Champlain (LC) and the Richelieu River (RR) at the Saint Jean Marina. The water levels were based on using the HYDROTEL Lake Champlain NBSs as input to Environment and Climate Change Canada's daily time step version of the Lake Champlain water balance model (WBM).

This study first quantifies the hydrological services provided by the 1,551 km^2 of existing wetlands located in the LC basin (covering 7% and draining 37% of the basin) and illustrates their role in the attenuation of NBS, peak flows, and water levels. These effects were observed both during the 2011 flood and in theoretical simulations (i.e., the four watershed storage scenarios) using 64 years of meteorological data. Results demonstrate that existing wetlands can reduce, on average, the annual high flow of the 20 LC tributaries by 9% up to 52%. These reductions then reduce the LC annual NBS high flow by 22%, the RR annual high flow by 6%, the LC annual high water level by 12 cm and the RR annual high water level by 9 cm. Also, existing wetlands contribute to low flow amplifications.

The four watershed storage scenarios (corresponding to additional storage areas of 2,256 km^2 of flooded farmland, 647 km^2 of wetlands, 865 km^2 of wetlands, and 1,488 km^2 of wetlands) highlighted the potential of achieving additional gains to reduce LC NBSs and water levels, and to a lesser extent the RR peak flows and water levels. Also, for completeness sake, the storage scenarios demonstrate the ensuing impacts on low flows, mostly amplification (increasing) but sometimes attenuation (reducing), the former being a sought-after hydrological service.

Table ES-1 introduces the average reductions in high flows and water levels as a result of each of the four storage scenarios. Note that Table ES-1 presents averages and does not reflect results for individual events of varying intensity and duration.

Table ES-1-1. Average reduction in high flows and water levels as a result of each of the four storage scenarios.

Scenario	Average reduction in tributary high flows (%)	Average reduction in LC NBS high flow (%)	Average reduction in annual RR high flow (%)	Average reduction in annual LC high water level (cm)	Average reduction in annual RR high water level (cm)
Water storage on riparian agricultural land	1 - 49	15	2	4	3
Construction/ restoration of wetlands based on spatial data	0.7 - 13	6.3	2.6	5	3
Construction of wetlands on US EPA-identified lands	0.9 – 26.6	8.1	2.6	5	3
Combining wetlands construction scenarios	2.6 – 28.1	12.7	4.7	8	6

From a pure hydrological modelling point of view, additional wetlands based on the combined large-scale scenario could substantially contribute to flood attenuation and be an effective passive water storage practice. However, adding wetlands and/or flooding farmland would involve extensive surface area requirements. Given existing policies, programs and regulations in Canada (e.g., Quebec Bill 132 - An Act respecting the conservation of wetlands and bodies of water) and/or in the United States (e.g., programs managed by the USDA Natural Resources Conservation Service, US Fish and Wildlife Service, and Vermont and New York States' Departments of Environmental Conservation), fostering restoration and construction of wetlands instead of flooding farmland might provide a socially-acceptable framework to build resilience over time in the LCRR basin, at least at the local subwatershed levels. The amount of land required to make a substantial impact on flows and water levels might be cost-prohibitive, and this may not be a viable solution. However, it is important to note that a cost-benefit analysis was beyond the scope of this study and underlying mandate. Nevertheless, the outcomes of this hydrological modelling exercise provide guidance to policy makers.

Finally, one of the legacies of the project is a new tool available in PHYSITEL to identify potential water storage areas given a pre-estimated runoff volume to be stored.

The LCRR HYDROTEL modelling project is available to assess multiple upland storage scenarios for each LC subwatershed, but ultimately for any scenario, there is a need to conduct comprehensive studies, including:

- a flood inundation mapping investigation throughout the LCRR basin using the output of HYDROTEL (i.e., simulated flows) as input to a hydraulic model to assess the potential impact of reducing the water levels by specified amounts in the LC and RR, respectively;
- an assessment of the effect on low flows; and
- a cost-benefit analysis including total costs (e.g., construction, easement payments, etc.) and total benefits (e.g., avoided damages, valuing environmental goods and services, etc.).

The outputs of this study quantify the flow and water level impacts of alternative scenarios to standard flood mitigation infrastructures such as building dikes and dams, illustrating how various upland storage scenarios based on construction or restoration of wetlands or flooding riparian agricultural land could contribute to flood relief at the scale of the LC tributaries and the LCRR basin.

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.

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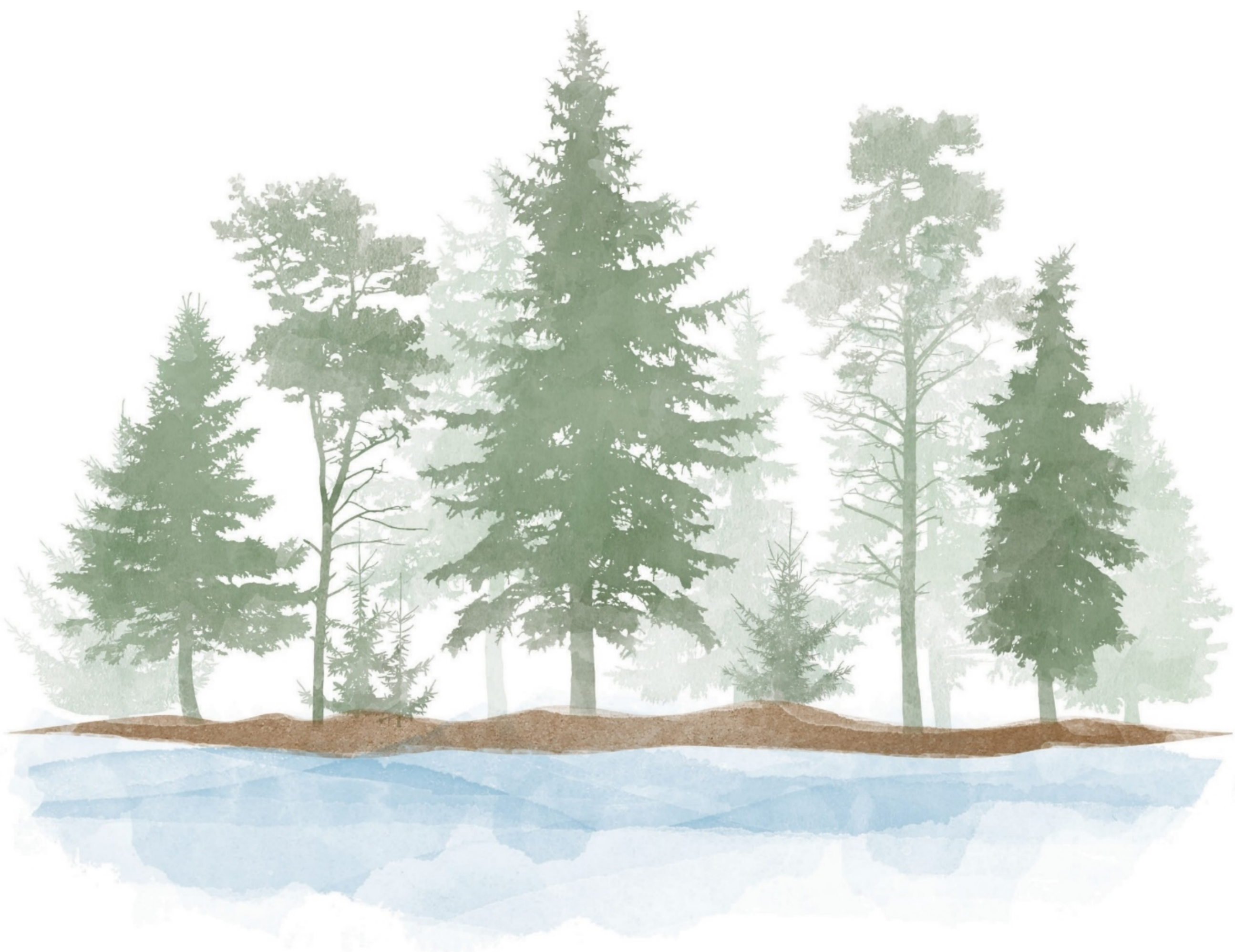


TABLE OF CONTENTS

List of Figures

Appendix II

Appendix III

List of Tables

Appendix II

1 INTRODUCTION TO THE REPORT

This report documents the study to assess the effect of various upland storage scenarios based on construction or restoration of wetlands or flooding riparian agricultural land on the flows of LC tributaries and RR as well as inflows to LC and ensuing water levels in the LC and RR.

The Richelieu River (RR) and Lake Champlain (LC) subwatersheds make up the Lake Champlain-Richelieu River (LCRR) basin. According to the IJC (2013), about 16% of the 23,800-km^2 LCRR basin lies in Canada and 84% in the USA. The RR subwatershed contributes to roughly 10% of the annual discharge into the St. Lawrence River, while the total discharge flowing out of LC contributes the remaining 90% (IJC, 2013). Saad et al. (2016) reported that large amounts of snowfall during the 2010-2011 winter, high snowmelt rates, sustained high-intensity rainfall events during the 2011 spring, and strong and sustained southerly winds in the Lake Champlain valley combined to produce the record spring flood. Riboust and Brissette (2016) further assessed that the total precipitation in April and May of 2011 and the maximum snowpack had return periods larger than 500 years and 15 years, respectively. According to the IJC (2013), regardless of these statistical assessments, communities north of LC and along the RR suffered considerable economic losses, with 79%, 10% and 11% of the losses occurring in Québec, Vermont and New York, respectively.

There exist two approaches to flood mitigation for protecting critical areas in the LCRR basin:

1. allowing water to naturally be reconnected with flood plain as stage rises above river banks or shorelines (i.e., active-passive storage);

2. allowing water to be retained naturally into specific landscapes or water bodies (i.e., passive storage); and (2) directing water through the use of gates, dikes, canals and other structures to ensure a pre-determined amount is conveyed to pre-delineated lands and away from areas to be protected (i.e., active storage).

When both active and passive approaches are considered, the active one complements the passive one. Restoration of wetlands on the LCRR landscapes has also been discussed as a passive storage approach to reduce both peak flows (e.g., Fossey et al., 2016a,b,c) and to a lesser extent, runoff volumes (e.g., Blanchette et al., 2019). Indeed, distributed hydrological modelling studies have shown that wetlands generally reduce flows on the rising limb, dampen the peak flow and slightly increase flows on the recession limb of a storm hydrograph. This has also been observed, not only simulated. Indeed, Price et al., (2005) provided a review in the Canadian context while Cole et al. (1997) reported similar observations.

In the LC basin, there is a well-documented, exceptional event that clearly showed that wetlands can alleviate flooding, namely the Otter Creek watershed between Middlebury and Rutland, Vermont. During Tropical Storm Irene in August 2011, wetlands and floodplains protected Middlebury from as much as US$1.8 million in flood damage (Watson et al., 2016). A study focused on the Otter Creek watershed (Watson et al., 2016) was the first to calculate the economic benefits that wetlands and floodplains provided during the major storm that struck the US East Coast in recent years.

Researchers analyzed 10 flood events to estimate the value of the Otter Creek floodplain and determined that the natural barrier saves the town of Middlebury an average of US$126,000 to $450,000 per year, or up to 78 percent of potential damages.

Using the aforementioned background information in part, the general objective of this study was to assess the effect of various upland storage scenarios based on construction or restoration of wetlands or flooding riparian agricultural land on the flows of LC tributaries and RR as well as inflows to LC and ensuing water levels in the LC and RR.

2 OBJECTIVES

The main objective of this study was to assess the effect of combined passive-active approaches of flood mitigation methods in the LCRR basin; that is, assessing the potential of:

1. storing flood water on riparian agricultural landscapes; and
2. using current, restored, and constructed wetlands of tributaries of the Vermont and New York States' subwatersheds to reduce runoff volumes, peak flows and net basin supplies to Lake Champlain.

The first approach can be viewed as the active approach in the sense that it would imply directing runoff and flows over river banks through dikes. However, since dikes were not explicitly modelled in this project, this approach is better classified as a pseudo-active approach.

Appendix I provides a listing of tasks completed in 2019 and 2020 for this effort.

3 METHODOLOGY

The aforementioned objectives focusing on the assessment of the effect of combined passive-active approaches were met by performing seven (7) major work packages, namely:

1. Adapting the current implementation of HYDROTEL on the LCRR basin - supported by the Flood Management and Mitigation Measures (FMMM) group - along with all datasets used to develop an updated database using PHYSITEL and achieve a current hydrological modelling of the LCRR basin. It was important to start with the same database, but there was also a need to update the FMMM PHYSITEL/HYDROTEL (Lucas-Picher et al., 2020) project with more recent or higher spatial resolution data.

2. Parameterization of all wetlands given the most recent land cover map followed by calibration and validation of HYDROTEL using an optimization software tool (OSTRICH).

3. Construction of an upland storage scenario focussing on storing flood water on riparian agricultural landscapes using stream network and agricultural field proximity.

4. Construction of various wetland construction/restoration scenarios using a priori a simplified approach based on topographical data (i.e., DEM, Land Cover Map) and an existing relevant scenario; that is the Wetland Protection and Restoration scenario developed by the United States Environmental Protection Agency (EPA).

5. Using HYDROTEL to assess the potential attenuation of high flows provided by current wetland distribution, as well as constructed or restored wetland scenarios or riparian agricultural landscape water storage scenarios for all the major tributaries of the LCRR subwatersheds.

6. Using both HYDROTEL Lake Champlain net basin supply results and Lake Champlain daily Water Balance Model (WBM) to assess the impacts of current wetland distribution as well as constructed or restored wetland scenarios or riparian agricultural landscape water storage scenarios on Lake Champlain water levels and Richelieu River flows and water levels.

7. Evaluation of the potential water storage capacity provided by agricultural land using either the DEM or the HAND algorithm (Nobre et al., 2016) of the major tributaries of the LCRR basin and using PHYSITEL mapping of potential areas to store water away from areas to be protected.

These activities are described in the following chapters of this report.

4 DATA COLLECTION/ TRANSFER AND PROCESSING USING PHYSITEL

PHYSITEL is a specialized geographic information system (GIS) (Turcotte et al., 2001; Rousseau et al., 2011; Royer et al., 2006) that has been developed to determine the complete drainage structure of a watershed using a Digital Elevation Model (DEM) and digitized river and lake networks. HYDROTEL is a distributed hydrological model that simulates stream flows and state variables such as snow water equivalent and water saturation using basic meteorological variables. The DEHQ[1] previously built a PHYSITEL/HYDROTEL LCRR project that was used by researchers at ÉTS[2] for the simulation of the multi-year mean annual hydrograph and 2011 flood of the LCRR basin. Hence, the DEHQ provided the watershed limits, hydrographic network, and hydrometeorological database. For this study, a 30-m horizontal resolution was used, rather than DEHQ's 100-m spatial resolution, to take advantage of the availability of higher resolution land cover and wetland maps. Additional characterization of the basin by PHYSITEL required integration of a classified land cover map; soil texture map, based on percentage of sand, loam, and clay, along with corresponding hydrodynamic properties (Rawls and Brakensiek, 1989); and wetland attributes based on existing inventory maps.

Table 4.1 presents the information required for the distributed hydrological modelling of the LCRR basin using the HYDROTEL/PHYSITEL modelling platform.

Table 4-1. Spatial data for watershed discretization using PHYSITEL.

Input Data	Available Source
Digital elevation model (DEM)	United States Geological Survey (USGS) (30-m horizontal resolution)
Stream and lake networks	United States Geological Survey (USGS) *Réseau hydrographique du Québec (Énergie et Ressources naturelles Québec)*
Land Cover	National Land Cover Database (NLCD) 2016 (USGS) *Cartographie de l'occupation du sol des basses terres du Saint-Laurent 2018 (Données Québec, Gouvernement du Québec)*
Soil Type (Texture)	USGS General Soil Map (STATSGO2) Soil Landscape of Canada v3.2 (Canadian Government)
Wetlands	National Wetlands Inventory (U.S. Fish & Wildlife Service) *Cartographie détaillée des milieux humides 2017 (Données Québec, Gouvernement du Québec)*

Figure 4.1 to Figure 4.3 display LCRR basin maps of the input data introduced in Table 4.1.

[1] Direction de l'expertise hydrique du Ministère de l'Environnement et de la Lutte contre les changement climatiques du Québec
[2] École de Technologie Supérieure

Additional data requirements for hydrological modelling included:

- meteorological data measured at existing stations or reconstructed and distributed on a grid; and
- measured streamflow data by any hydrometric station on the stream network or reconstructed reservoir/lake inflows.

With the aforementioned geographic data, PHYSITEL was used to delineate the watershed into Relatively Homogenous Hydrological Units (RRHU), namely hillslopes, and river/lake segments that made up the computational domains of HYDROTEL. In other words, PHYSITEL determined the internal drainage structure (slopes and flow directions), watershed boundaries, subwatershed and hillslope boundaries, and hydrographic network.

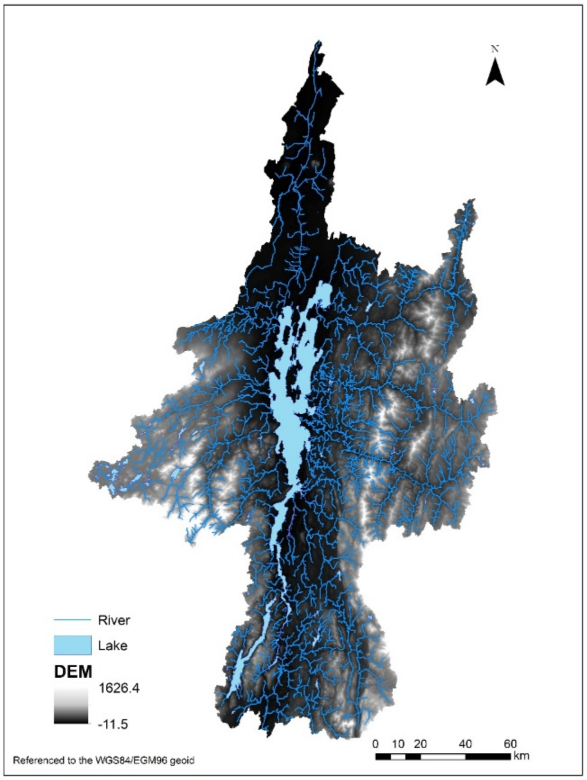


Figure 4-1. Digital elevation model (DEM) and stream and lake network.

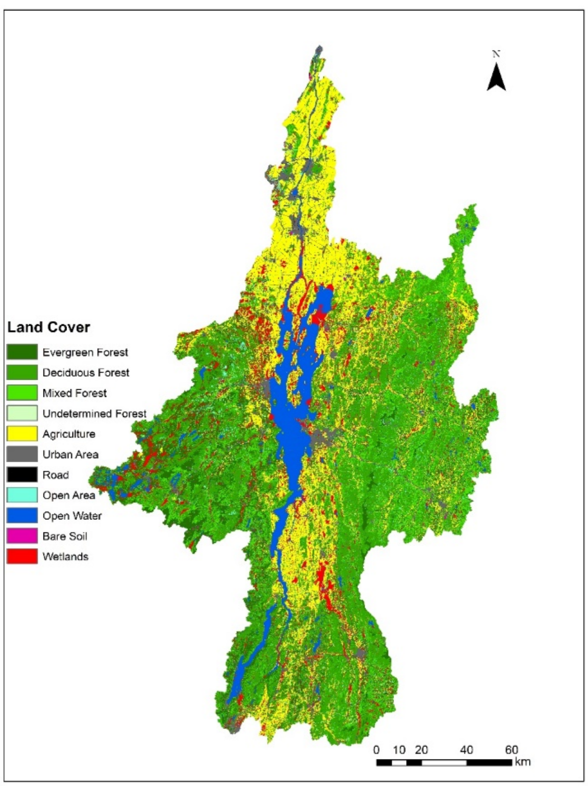


Figure 4-2. Land cover and wetlands inventory.

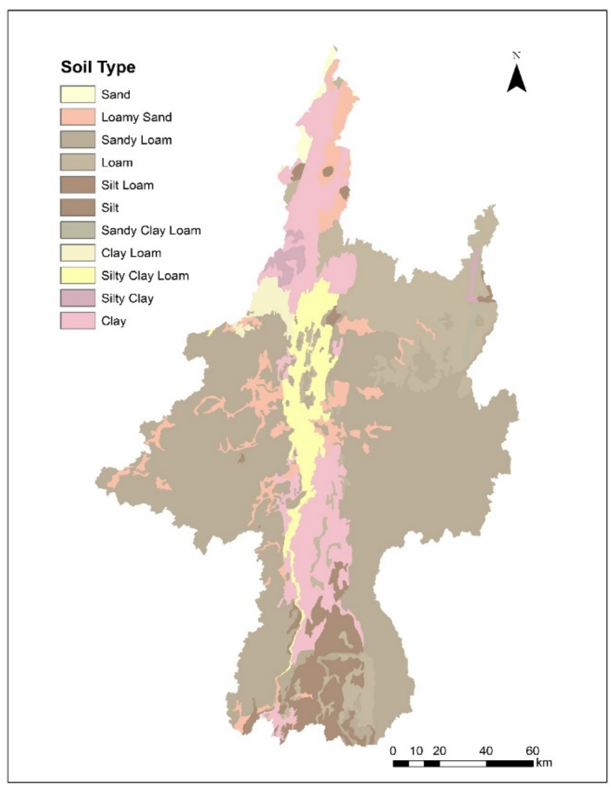


Figure4-3. Soil types.

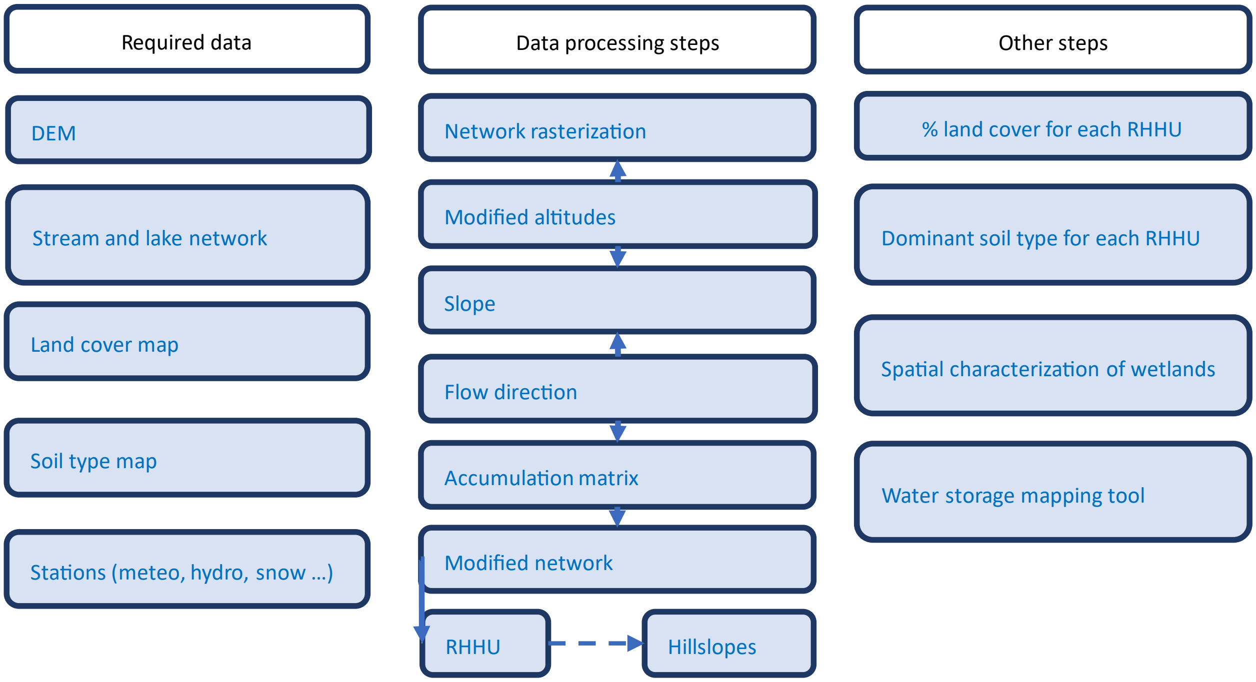


Figure 4-4. PHYSITEL – Input data and data processing.

For each RHHU, PHYSITEL calculated a topographic index and identified the dominant soil type, and percentages of different land covers. Figure 4.4 summarizes the various tasks performed by PHYSITEL.

PHYSITEL allowed for the spatial characterization of wetlands based on the available types of wetlands (see Figure 4.5) provided by the land cover map. In addition, PHYSITEL delineated isolated and riparian (based on a river connectivity threshold) wetlands and corresponding drainage areas.

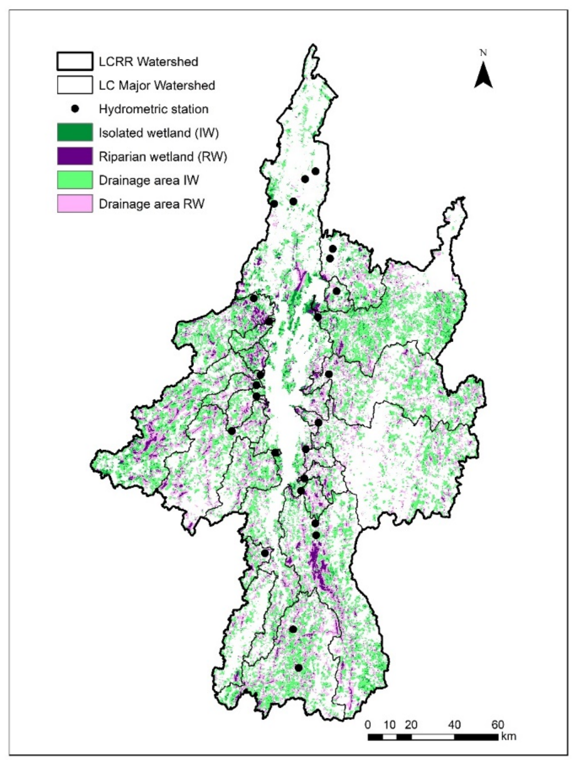


Figure 4-5. Drainage area and types (isolated and riparian) of wetlands in the LCRR watershed.

As a complement, Table 4.2 summarizes the cumulative drainage area of each type of wetlands within the LCRR and Lake Champlain (LC) basins In terms of total watershed area, the cumulative surface area and drainage area of wetlands of the LCRR basin are 7% and 34%, respectively; also, 92% of wetlands are located within the LC subwatershed. It is noteworthy that the drainage area does not include the wetlands area. Table 4.2 highlights that even a small aerial coverage of wetlands can drain a large fraction of a watershed. Section 5 presents a detailed table on wetland area and drainage area for all major LCRR major subwatersheds.

Table 4-2. Drainage area and surface area of each type of current wetlands within the LCRR and Lake Champlain (LC) basins.

	Area (km^2) (fraction of the watershed)	
Watershed	**LCRR**	**LC**
Total watershed	23,799 km^2	21,254 km^2
Isolated wetlands (IW)	945 km^2 (4 %)	849 km^2 (4 %)
Riparian wetlands (RW)	740 km^2 (3 %)	702 km^2 (3 %)
Total wetlands (TW)	1,684 km^2 (7%)	1,551 km^2 (7%)
Drainage area IW	5,537 km^2 (23 %)	5,254 km^2 (25 %)
Drainage area RW	2,561 km^2 (11 %)	2,495 km^2 (12 %)
Total drainage area	8,099 km^2 (34%)	7,749 km^2 (37%)

5 HYDROTEL CALIBRATION AND VALIDATION

From a hydrological modelling perspective, HYDROTEL (Fortin et al., 2001; Turcotte et al., 2003, 2007; Fossey et al., 2015) computes for each computational unit and reach, the following: the spatial distribution of meteorological conditions, evapotranspiration, snow accumulation/melt, infiltration, recharge, surface flow, subsurface flow and channel routing. These were computed using a daily time step for this study.

HYDROTEL includes specific modules to simulate the hydrological processes of each type of wetlands (isolated, riparian), accounting for the water budget at the scale of each RHHU. The wetland module simulates: water interception from precipitation, snow melt and runoff (surface and subsurface) from the contributing area (i.e. the wetland drainage area), evapotranspiration, percolation at the bottom of each wetland (contributing to base flow), water storage and outflow. For riparian wetlands, in addition to the aforementioned processes, the module simulates: direct water exchange and interaction with the adjacent river segment through overland runoff and river bank flow. Also at the scale of each RHHU, isolated or riparian wetlands are numerically grouped to form an equivalent wetland where the total area and drainage area of the isolated and riparian wetlands are summed up. More detailed description of the wetland module can be found in Appendix II or if needed the reader may consult the cited literature.

The hydrometeorological data included gridded or site-specific precipitation, daily maximum and minimum air temperatures, and, for model calibration, stream flows, reconstructed reservoir inflows and any other relevant state variables (e.g., snow water equivalent or SWE). As mentioned before, the computational domain consisted of interconnected river segments (RSs) and three-soil-layer hillslopes (i.e., RHHUs).

Figure 5.1 presents the computational units of the LCRR basin project of HYDROTEL.

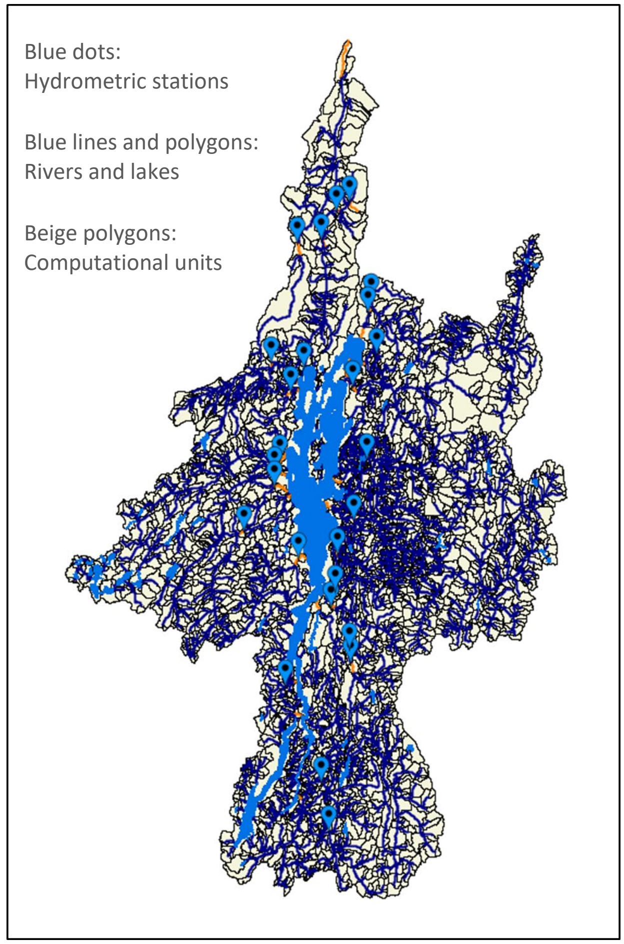


Figure 5-1. LCRR project of HYDROTEL (screen capture of the graphical user interface).

For this study, the LCRR was delineated into 8,473 RHHUs (i.e., hillslopes; avg. 2.81 km^2) and 3,289 river and lake segments (avg. 2.81 km; LC is 170-km long); that is the hydrological computational domain.

Hydrologic simulations were driven by gridded meteorological conditions from 1950 to 2013, with 690 grid points located within the watershed limits (data from Livneh et al., 2015). Model calibration and validation were based on 25 hydrometric stations (18 USGS, 6 DEHQ, 1 FGC) within the LCRR watershed. Quarter-monthly net basin supply (NBS) values were also available for Lake Champlain. Although HYDROTEL was calibrated to corroborate as well as possible the flows of the Richelieu River recorded at the Canadian Government Hydrometric Station (Aux Rapides Fryers, number 02OJ007), results for this specific site were based on using the HYDROTEL Lake Champlain net basin supply as input to ECCC's new daily time step version of the Lake Champlain water balance model.

Model calibration was first performed for the 1992-2003 period, and validation, for the 2004-2013 period. For a few hydrometric stations, due to a lack of data, calibration and validation periods differed and were identified by dividing the data availability period in two. Calibration was performed in a distributed fashion to corroborate observed flows as well as possible. For most of the subwatersheds, calibration was performed independently; meanwhile for the calibration of the most downstream river segment, the calibration benefited from the upstream calibrated subwatersheds. In order to assess and illustrate the impacts of all water storage scenarios on the worst known hydrological year, a specific calibration was then performed for year 2011.

Calibrations were performed using the Optimization Software Toolkit for Research Involving Computational Heuristics (OSTRICH; Matott, 2017), a model-independent multi-algorithm optimization and parameter estimation tool. Through the calibration process, the toolkit varied the model parameters to improve the fit between observed and simulated flows using a multi-objective function. Optimal parameter values for each subwatershed (at the hydrometric station site) were found using the Kling-Gupta Efficiency criterion (KGE) (Gupta et al., 2009), where one (1) represents the optimum value of the KGE, as the first and most relevant performance indicator and the mean squared error (MSE) as the second performance indicator.

Figure 5.2 presents the location of the 25 hydrometric stations within the boundaries of the LCRR watershed. Table 5.1 presents the calibration and validation results for the major tributaries of the Lake Champlain and Richelieu River focusing on KGE as the first performance indicator. Here the drainage area are reported for the hydrometric station upstream watershed. As mentioned previously, the calibration was performed to corroborate as well as possible the flows measured at Fryers Rapids, but the results introduced later in this report at this location were achieved by using the HYDROTEL Lake Champlain net basin supply as input to ECCC's new daily time step version of the Lake Champlain water balance model. The overall average values reported in Table 5.1 are weighted averages based on drainage areas.

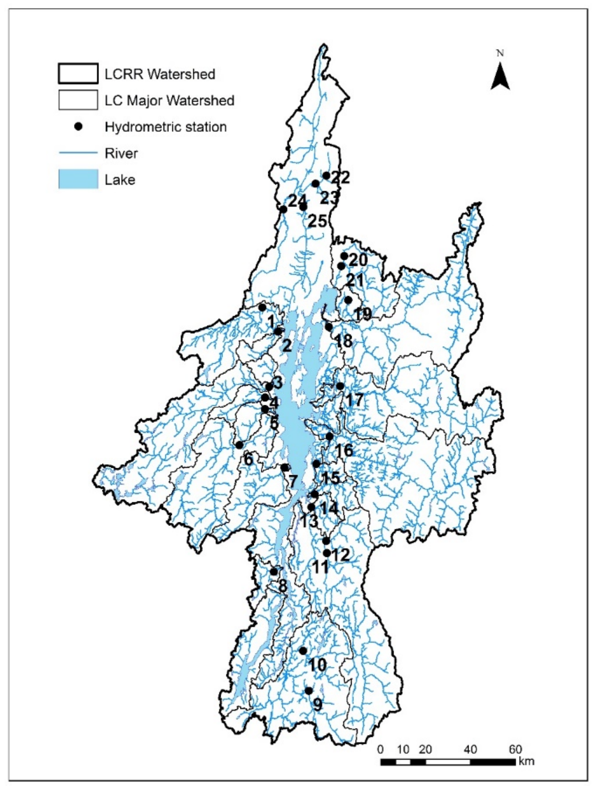


Figure 5-2. Location of the 25 hydrometric stations within the LCRR watershed.

Table 5-1. HYDROTEL calibration and validation results.

#	STATION	WATERSHED	DRAINAGE (km^2)	CALIBRATION		VALIDATION	
				PERIOD	KGE	PERIOD	KGE
1	4271500	GREAT CHAZY	648.73	1992-2003	0.80	2004-2013	0.68
2	4271815	LITTLE CHAZY	132.91	1992-2003	0.71	2004-2013	0.69
3	4273500	SARANAC	1568.49	1992-2003	0.89	2004-2013	0.72
4	4273700	SALMON	166.99	1992-2003	0.79	2004-2013	0.54
5	4273800	LITTLE AUSABLE	176.99	1992-2003	0.80	2004-2013	0.50
6	4275500	AUSABLE	1152.60	1992-2003	0.87	2004-2013	0.83
7	4276500	BOUQUET	614.17	1992-2003	0.80	2004-2013	0.83
8	4276842	PUTNAM CREEK	132.75	1992-2003	0.71	2004-2013	0.72
9	4280450	METTAWEE	431.20	1992-2003	0.79	2004-2013	0.61
10	4280000	POULTNEY	486.12	1992-2003	0.78	2004-2013	0.75
11	4282500	OTTER CREEK	1631.11	1992-2003	0.78	2004-2013	0.73
12	4282525	NEW HAVEN	301.43	1992-2003	0.78	2004-2013	0.77
13	4282650	LITTLE OTTER CREEK	152.46	1992-2003	0.60	2004-2013	0.73
14	4282780	LEWIS CREEK	194.71	1992-2003	0.74	2004-2013	0.76
15	4282795	LAPLATTE RIVER	114.25	1992-2003	0.69	2004-2013	0.63
16	4290500	WINOOSKI	2696.87	1992-2003	0.82	2004-2013	0.81
17	4292500	LAMOILLE	1781.09	1992-2003	0.87	2004-2013	0.83
18	4294000	MISSISQUOI	2203.59	1992-2003	0.79	2004-2013	0.74
19	0030425	DE LA ROCHE	81.60	2002-2007	0.67	2008-2013	0.52
20	0030423	MORPIONS	100.76	2000-2006	0.79	2007-2013	0.65
21	0030424	AUX BROCHETS	596.68	2002-2007	0.79	2008-2013	0.81
22	0030429	À L'OURS	24.47	2007-2010	0.55	2011-2013	0.39
23	0030415	DES HURONS	304.22	1992-2003	0.85	2004-2013	0.76
24	0030421	L'ACADIE	355.51	1992-2003	0.82	2004-2013	0.73
			WEIGHTED AVERAGE		0.82		0.76
25	***0030401***	***LCRR (FRYERS)***	***22054.83***	***1992-2003***	***0.88***	***2004-2013***	***0.92***

For most of the sites and subwatersheds with observations, results are deemed satisfactory; nonetheless, the large subwatersheds tend to have better results. Also, the results are consistent through time, as the validation results remain comparable to those of the calibration with a slight decrease (average KGE values decreasing from 0.82 to 0.76 from calibration to validation). For the SARANAC, SALMON, LITTLE AUSABLE, METTAWEE, DE LA ROCHE and À L'OURS subwatersheds, the performance decreases more drastically for the validation period while other subwatersheds, such as the BOUQUET and LITTLE OTTER CREEK, display an increase in performance. On the other hand, the modelling performance at FRYERS on the Richelieu River, downstream of Lake Champlain, is very good for both calibration (0.88) and validation (0.92), improving in the latter period.

To further investigate model performance, simulation results were compared with observed stream flows using three approaches and the two available model calibrations:

1. the sum of observations, namely subwatersheds 1 to 18 as identified on Figure 5.2; which essentially corresponds to major flows entering Lake Champlain (see first rows of Figure 5.3 and Figure 5.4);

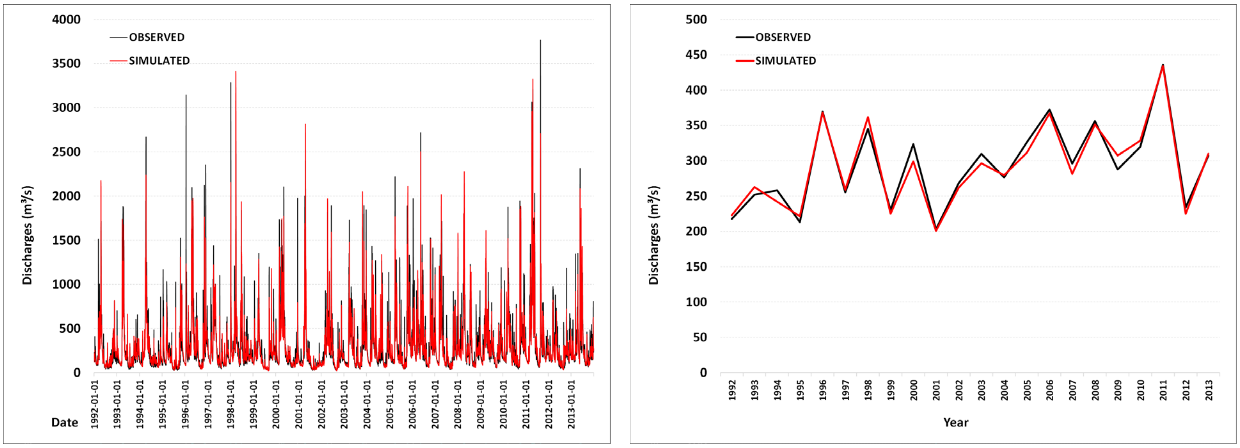
2. an estimation of the Lake Champlain net basin supply (NBS, which is made up of inflows from all rivers discharging into the lake, while accounting for precipitation over the lake, and lake evaporation) from Environment and Climate Change Canada (ECCC; Boudreau et al., 2018) using a quarter-monthly time step (second row of Figure 5.3 and Figure 5.4); and

3. as a complement, a comparison of simulated and observed Richelieu River flows, downstream of Lake Champlain, at the Aux Rapides Fryers (Fryers Rapids station) hydrometric station (see last rows of Figure 5.3 and Figure 5.4) based on the newest daily Lake Champlain Water Balance Model (WBM) using HYDROTEL NBS as input.

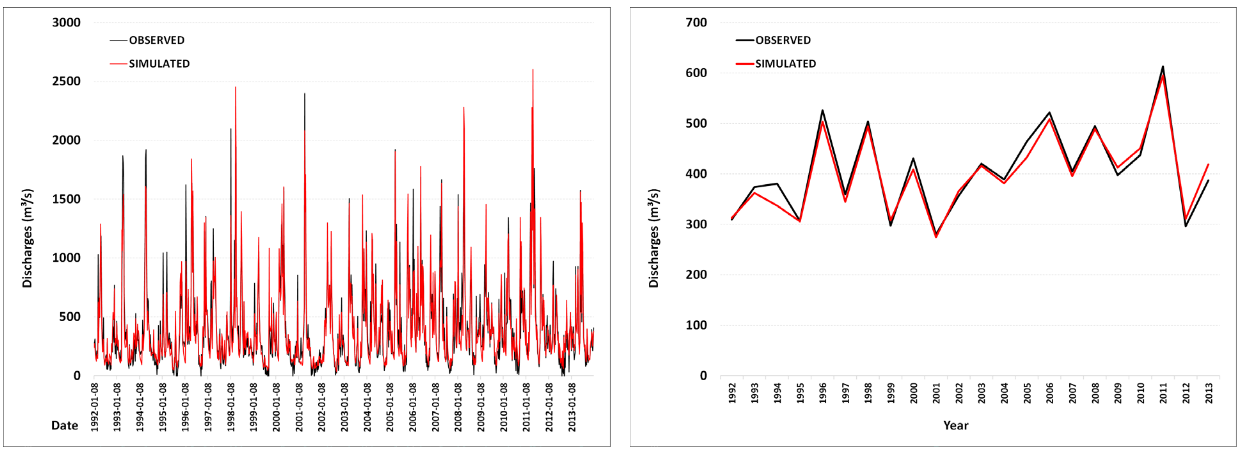
Looking at the 1992-2013 time series of the river flows of the 18 Lake Champlain subwatersheds (referred to as sum-18 (top left graph of Figure 5.3), a consistent pattern can be seen, with a maximum in spring and minimum in summer. High flows can also be observed during fall due to heavy precipitation, or in winter during warm spells. The KGE value of 0.93 between the simulated and observed sum-18 reflects a good simulation of the river flows of the 18 subwatersheds considered. On an annual basis, the inter-annual variations of the sum-18 are also well simulated by HYDROTEL, with a KGE value of 0.98 and a +0.6% bias (top right graph of Figure 5.3). The simulated 1992-2013 average annual hydrograph for the sum-18 corroborates well with observations, with a KGE value of 0.95 (top left graph of Figure 5.4). The freshet period, with flow peaking in April, can be clearly seen with an average inflow of about four to five times that in summer. The large and continuous lake inflows during the months of March, April and May 2011, which led to the flood, are clearly displayed in the top right graph of Figure 5.4. Moreover, the very intense, but short duration inflow at the beginning of September 2011 caused by Hurricane Irene is also captured by HYDROTEL. Specific to year 2011, a KGE value of 0.96 +0.4% bias was deemed excellent for the sum-18 comparison.

Also, there is a good match between the simulated and ECCC-estimated NBSs from 1992 to 2013 at a quarter-monthly time step, with a KGE value of 0.94. Again, the inter-annual variations are well represented, with a KGE value of 0.93 and a bias of +1.4%. For the 1992-2013 average annual hydrograph of Figure 5.4 (left center row graph), the simulated NBS is close to that observed, with a KGE value of 0.92. For the year 2011, the KGE value remains high, with a value of 0.93. The simulated average annual hydrograph of NBSs shows slight underestimation during the winter period and the high flow period of April and May except for the peak period, while the average low flow is slightly overestimated in August and September. In Figure 5.4, the simulated 2011 peaks of the quarter-monthly time series of NBSs are sometimes underestimated or overestimated.

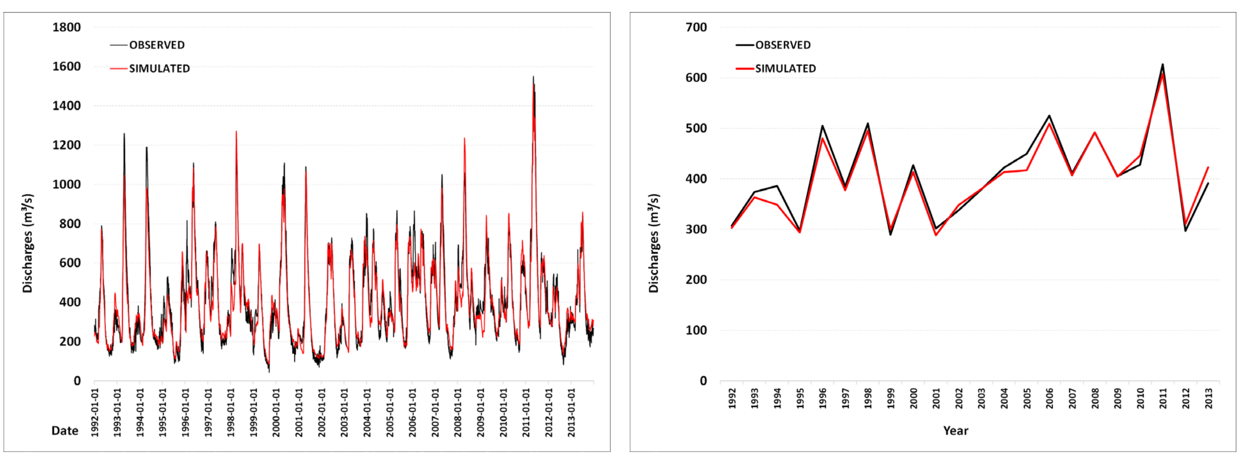
(a) Sum of river flows of the 18 sub-watersheds of Lake Champlain



(b) Lake Champlain NBS



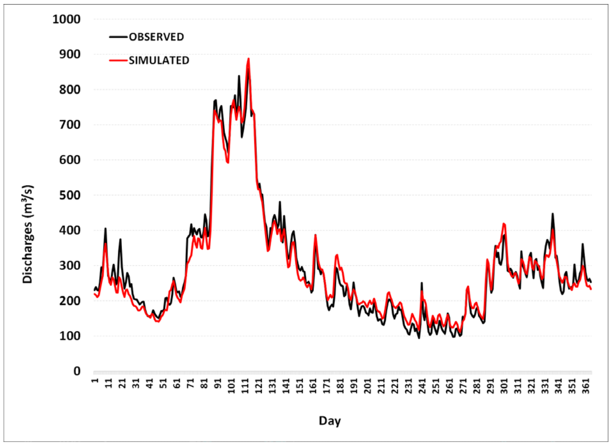
(c) Richelieu River flows at Fryers Rapids station

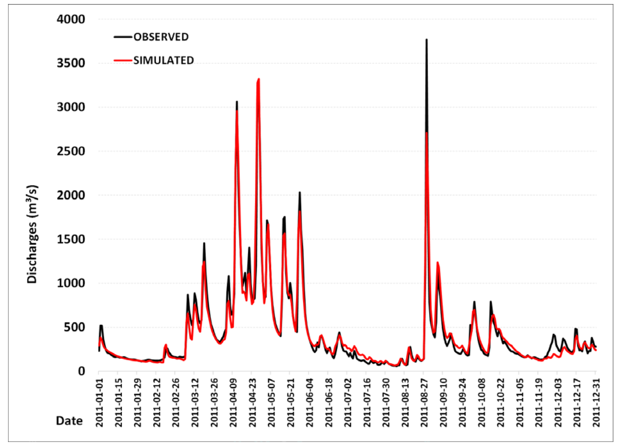


**Observations are displayed in black and simulations in red.*

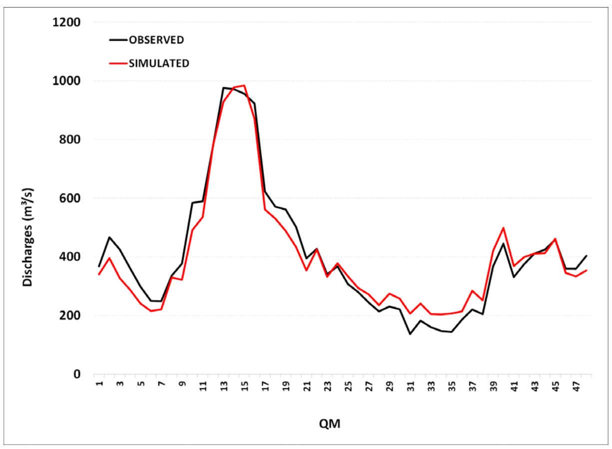
Figure 5-3. Daily (left) and annual (right) time series (1992-2013) of observed and simulated flows and net basin supplies (NBS).

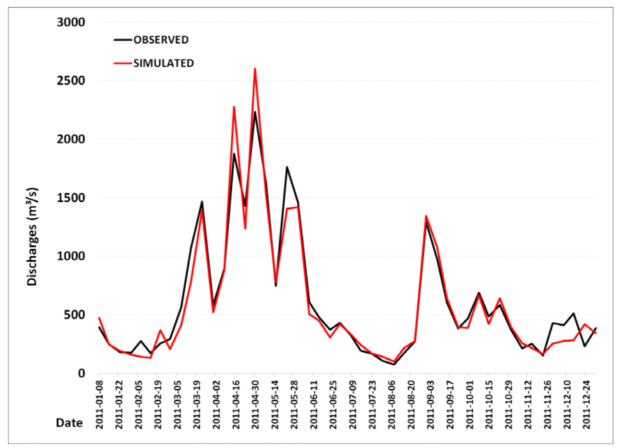
(a) Sum of river flows of the 18 sub-watersheds of Lake Champlain



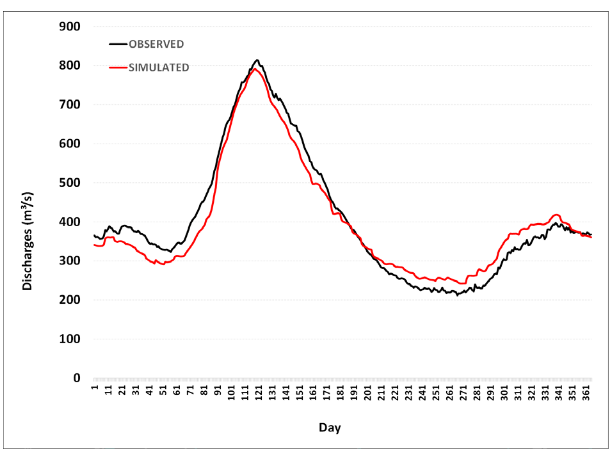


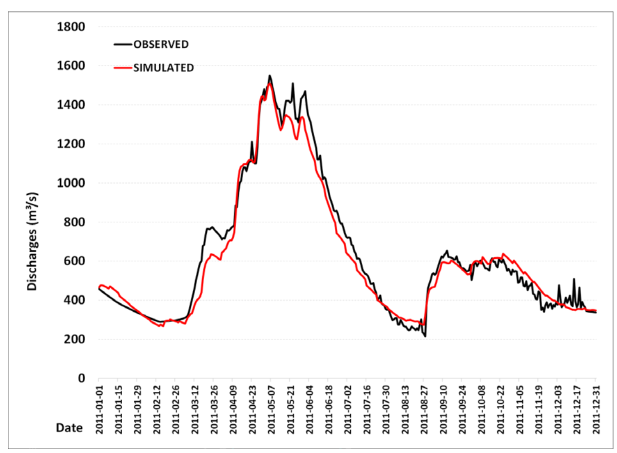
(b) Lake Champlain NBS





(c) Richelieu River flows at Fryers Rapids station





**Observations are displayed in black and simulations in red.*

Figure 5-4. 1992-2013 average annual hydrograph (left) and 2011 hydrograph (right) of observed and simulated flows and net basin supplies (NBS).

To complete the analysis, the simulated and observed Richelieu River flows downstream of Lake Champlain, at Fryers Rapids station, can be compared. The KGE value for the 1992-2013 daily time series (bottom left graph of Figure 5.3) is similar to those of the sum-18 and the NBS, with a value of 0.90 and a bias of 1.3%. Inter-annual variations of the annual average are still well simulated by the Lake Champlain daily WBM using HYDROTEL NBS as inputs, with a KGE value of 0.93 (bottom right graph of Figure 5.4). For the average annual hydrograph at Fryers Rapids station (bottom left graph of Figure 5.4), the average freshet in April and May is well represented, but the winter low flows are underestimated and average late-summer low flows in August and September are overestimated.

Considering those differences, the KGE value of 0.88 for the average annual hydrograph and 0.92 for year 2011 (bottom right graph of Figure 5.4) are still acceptable and generally viewed as good. Considering the 2011 flood, combining HYDROTEL and ECCC's WBM slightly underestimated the observed peak flow of 1,550 m^3/s by 40 m^3/s in early May at Fryers Rapids station. Simulating flows at Fryers Rapids station remains a challenge due to the upstream Lake Champlain water storage and routing effect.

Finally, additional uncertainties are in all likelihood linked to the gridded meteorological forcing and the simulated flows of the other tributaries of the Lake Champlain or the Richelieu River that were not calibrated explicitly due to missing observed continuous flow records.

6 EFFECT OF CURRENT WETLANDS ON STREAM FLOWS

Located at the interface between terrestrial ecosystems and water resources such as water courses and shallow water tables, wetlands are part of the drainage network. Consequently, they affect the routing of overland and subsurface flows through modification of hydrological processes, namely increased evapotranspiration, water storage and groundwater recharge (Bullock and Acreman 2003). These interactions have led researchers and land planners to link some hydrological services to wetlands, namely flow regulation as highlighted by amplifying low flows and attenuating high flows.

Existing wetlands within the LCRR watersheds provide hydrological services that are highly relevant to stakeholders involved in water resources management and wetlands protection/conservation programs. Over the past five years, the wetland modules available in HYDROTEL have been used extensively to evaluate such hydrological services (e.g., Fossey et al., 2015, 2016a,b,c, Blanchette et al., 2019, Wu et al., 2020a,b). More information on the HYDROTEL wetland modules can be found in Appendix II.

For watersheds with recurrent floods, the natural water storage capacity of wetlands becomes an important asset. To evaluate the hydrological services provided by the current spatial distribution of wetlands in the LCRR basin, the study team used a simple comparison approach based on two distinct hydrological simulations, one with the wetland modules turned on and another with the wetland modules turned off. Without the wetland module, wetlands behave more like saturated soils, without any buffering capacity. Both long-term simulations were performed using daily meteorological data time series covering the 1950-2013 period. The with- and without-wetland simulations comparison allowed isolation of the flow regulation services provided by wetlands, namely attenuation of high flows and amplification of low flows.

The hydrological services were assessed as follows:

- For high flows:
  $$\frac{Without\ Wetlands - Current\ Wetlands}{Without\ Wetlands}$$
  where a positive result corresponds to a high flow attenuation.

- For low flows:
  $$\frac{Current\ Wetlands - Without\ Wetlands}{Without\ Wetlands}$$
  where a positive result corresponds to a low flow amplification.

To quantify the high flow attenuation services, the relative variations on annual, spring and fall maximum flows were calculated, based on a continuous with- and without wetland long term hydrological simulation covering years 1950 to 2013, while the low flow amplification services were assessed by calculating the relative variation on annual, spring and fall minimum 7-day low flows. Also, the flow inter-comparison was performed on similar flow events to prevent erroneous comparisons.

Figure 6.1 presents the 20 major gauged and ungauged subwatersheds of the LC watershed; Table 6.1 (see page 18) introduces the wetland area and associated drainage area for each of these subwatersheds.

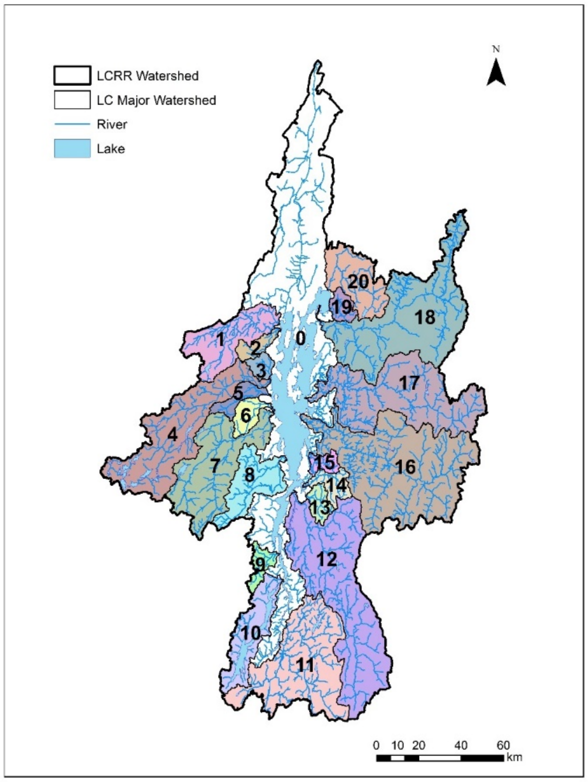
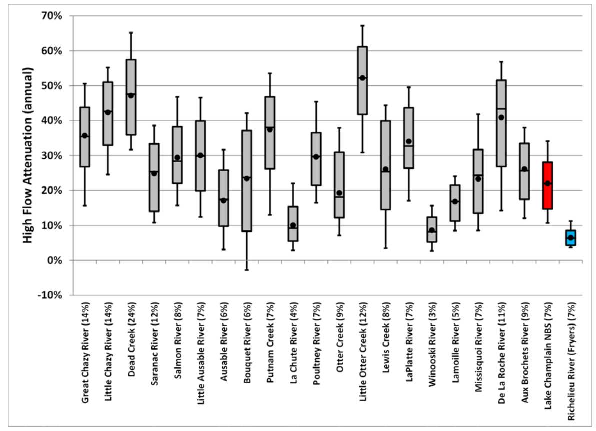


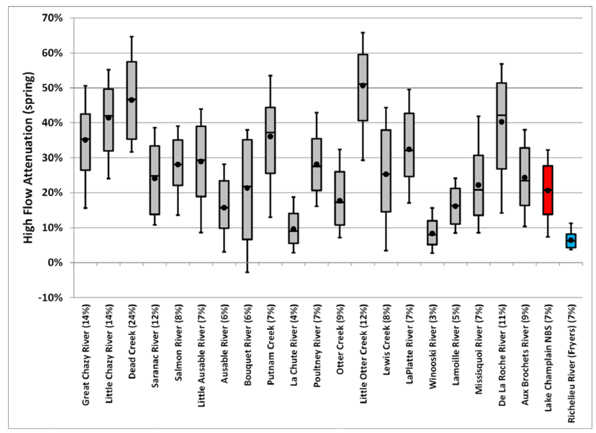
Figure 6-1. Major LC subwatersheds (>100 km²).

6.1 EFFECT OF WETLANDS ON HIGH FLOWS

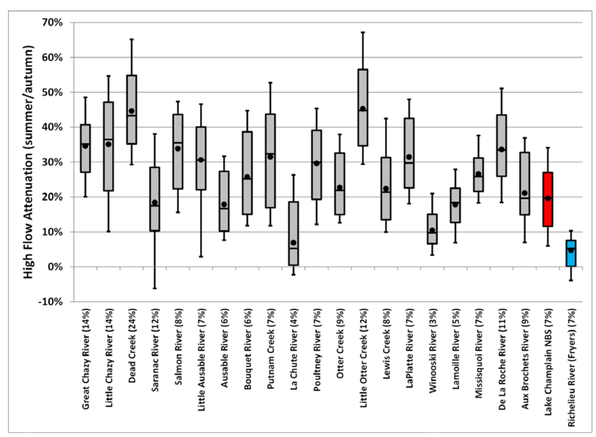
Figure 6.2 highlights the impact of the current distribution of wetlands on high flows on an annual basis (Figure 6.2a), and for spring (Figure 6.2b) and summer/fall (Figure 6.2c). As this study places emphasis specifically on high flows and flood risk, the impact of the current distribution of wetlands on low flows is not discussed here; however, these results are reported in Appendix III (Figure A3.1). Table 6.2 (see page 19) summarizes the annual impact of current wetlands on (i) high flows for the 20 major LC subwatersheds, (ii) LC NBS, (iii) RR flows at Fryers Rapids, and (iv) LC and RR (Marina Saint-Jean) water levels based on the use of HYDROTEL NBS as input to the daily Lake Champlain WBM. Also, Table 6.2 includes the impacts on high flows for specific years.



(a) (Min; Max; 10th percentile; 90th percentile; Median; Average)



(b) (Min; Max; 10th percentile; 90th percentile; Median; Average)



(c) (Min; Max; 10th percentile; 90th percentile; Median; Average)

Figure 6-2. Impacts of current wetlands on high flow attenuation of the 20 LC subwatersheds, LC NBS and RR flows at Fryers Rapids for various temporal scales: (a) annual, (b) spring and (c) summer/fall.

Table 6-1. Description of wetlands area and wetlands drainage area for the 20 LC subwatersheds, LC and LCRR at Fryers Rapids watersheds.

#	WATERSHED	DRAINAGE (km²)	WETLANDS		WETLANDS DRAINAGE	
			(km²)	(%)	(km²)	(%)
1	Great Chazy	778	107	13.8%	371	47.6%
2	Little Chazy	143	20	14.2%	73	50.9%
3	Dead Creek	114	27	24.0%	63	55.3%
4	Saranac	1,579	184	11.6%	761	48.2%
5	Salmon	177	15	8.3%	90	51.0%
6	Little Ausable	188	13	6.7%	94	50.2%
7	Ausable	1,329	76	5.7%	500	37.6%
8	Bouquet	621	38	6.1%	255	41.1%
9	Putnam Creek	158	12	7.5%	81	51.4%
10	La Chute	678	25	3.7%	174	25.7%
11	Poultney	1,778	120	6.8%	775	43.6%
12	Otter Creek	2,446	224	9.1%	962	39.3%
13	Little Otter Creek	153	18	11.8%	79	51.9%
14	Lewis Creek	203	16	7.8%	80	39.6%
15	LaPlatte	118	8	6.7%	43	36.5%
16	Winooski	2,756	79	2.9%	658	23.9%
17	Lamoille	1,866	94	5.0%	707	37.9%
18	Missisquoi	2,212	155	7.0%	886	40.1%
19	De La Roche	144	15	10.7%	62	43.0%
20	Aux Brochets	664	57	8.5%	218	32.8%
	LC	**21,254**	**1,551**	**7.3%**	**7,749**	**36.5%**
	LCRR (Fryers)	**22,055**	**1,616**	**7.3%**	**7,902**	**35.8%**

Table 6-2. Impacts of current wetlands on high flows of the 20 LC subwatersheds, LC NBS, RR flows at Fryers Rapids and LC and RR (Saint-Jean Marina) water level.

#	WATERSHED (WT %)	MIN		MAX		FLOODED YEAR					AVERAGE	MEDIAN
		YEAR	ATTENUATION	YEAR	ATTENUATION	1973	1983	1984	2011	2013		
1	Great Chazy (14%)	1994	16%	2002	51%	31%	29%	24%	40%	50%	36%	35%
2	Little Chazy (14%)	2008	25%	1974	55%	41%	44%	35%	41%	55%	42%	43%
3	Dead Creek (24%)	1994	32%	1996	65%	47%	56%	43%	57%	62%	47%	48%
4	Saranac (12%)	1980	11%	1990	39%	13%	23%	25%	35%	32%	25%	25%
5	Salmon (8%)	1952	16%	1996	47%	29%	30%	23%	34%	36%	29%	28%
6	Little Ausable (7%)	1980	12%	1977	47%	30%	24%	31%	43%	36%	30%	30%
7	Ausable (6%)	1958	3%	1996	32%	20%	5%	12%	7%	19%	17%	17%
8	Bouquet (6%)	2001	-3%	1996	42%	28%	22%	21%	23%	28%	23%	24%
9	Putnam Creek (7%)	1952	13%	1974	54%	36%	26%	27%	38%	32%	37%	38%
10	La Chute (4%)	2012	3%	1995	22%	8%	6%	12%	9%	16%	10%	9%
11	Poultney (7%)	1997	16%	1996	45%	27%	30%	33%	32%	34%	30%	30%
12	Otter Creek (9%)	1958	7%	1964	38%	17%	10%	22%	28%	17%	19%	18%
13	Little Otter Creek (12%)	1953	31%	2011	67%	46%	41%	60%	67%	51%	52%	52%
14	Lewis Creek (8%)	1958	3%	1970	44%	27%	28%	32%	42%	31%	26%	25%
15	LaPlatte (7%)	2001	17%	1996	50%	33%	33%	26%	40%	25%	34%	33%
16	Winooski (3%)	1961	3%	1984	16%	12%	9%	16%	14%	9%	9%	8%
17	Lamoille (5%)	1971	8%	1962	24%	21%	16%	17%	17%	20%	17%	17%
18	Missisquoi (7%)	1954	9%	2002	42%	30%	25%	20%	16%	33%	23%	24%
19	De La Roche (11%)	1976	14%	1996	57%	29%	44%	54%	43%	44%	41%	43%
20	Aux Brochets (9%)	1953	12%	2006	38%	21%	29%	33%	33%	29%	26%	26%
	LC NBS (7%)	**1991**	**11%**	**1996**	**34%**	**17%**	**22%**	**23%**	**14%**	**26%**	**22%**	**22%**
	RR (Fryers) (7%)	***1974***	***4%***	***1998***	***11%***	***5%***	***5%***	***6%***	***6%***	***4%***	***6%***	***6%***
	LC Water Level (cm)	***1985***	***6***	***1998***	***26***	***14***	***9***	***12***	***15***	***10***	***12***	***11***
	RR Water Level (cm)	***1966***	***4***	***1998***	***21***	***8***	***8***	***8***	***12***	***6***	***9***	***8***

Generally speaking, for small subwatersheds with a high percentage of the watershed drained by wetlands (noted as WT % in Table 6.2), a significant impact on high flows was observed, when compared to large subwatersheds with smaller percentages of wetlands and drainage area. Also, the spatial distribution of wetlands within a watershed can have a major impact on high flow attenuation. Figure 6.2 clearly demonstrates a range of impacts on high flows. Individual-year impacts are not equivalent, as illustrated by the attenuation distribution of each subwatershed, as shown by the range of attenuation values for the individual subwatersheds.

Moreover, it is consequent that annual impacts and spring impacts are similar since the highest flow occurs most of the time during the spring freshet. Figure 6.2 shows that for only one subwatershed (Bouquet River), the annual or spring results include negative impacts (increase of high flows) and for two subwatersheds (Saranac and La Chute River), fall results include negative impacts. Results demonstrate a clear annual consistency in wetlands relative impacts on high flows. Also rare cases of negative impacts can occur from singular conditions (namely antecedent water level and soil moisture conditions) in wetlands prior to the occurrence of high flows. Table 6.2 shows variable maximum- or minimum-year impacts and contributions of current wetlands for specific years (1973, 1983, 1984, 2011, 2013).

Overall, the current distribution of wetlands reduces high flow NBS to Lake Champlain by 22%. Downstream of the damping effect of LC, wetlands still have a lingering effect and thus can reduce high flows by 6% on the Richelieu River at Fryers Rapids. These results clearly illustrate the high flow regulation services provided by the current distribution of wetlands in the LCRR watershed.

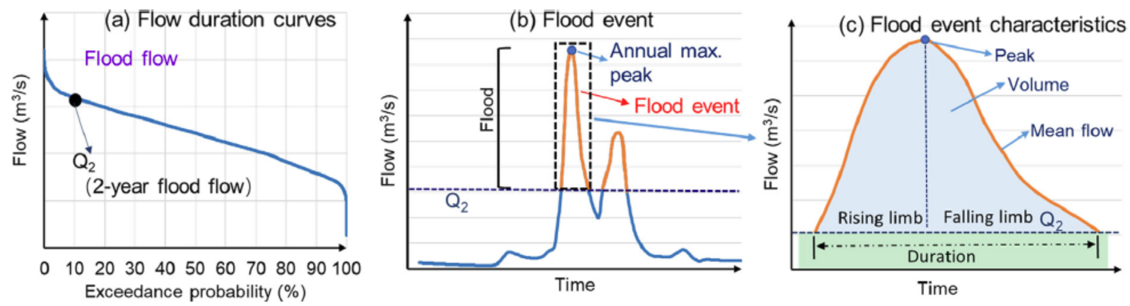
6.2 EFFECT OF CURRENT WETLANDS ON HIGH FLOW HYDROGRAPH

The study also analysed how wetlands can affect flood in terms of four indicators, namely peak flow, mean flood event flow, duration, and flow volume of high flow events.

A quantitative assessment of the effects during the rising and falling limbs of the event hydrograph was developed to identify whether or not the services were altered. A two-year return period high flow threshold (Figure 6.3(a)) was selected to assess all indices, because this threshold is often used as a proxy to bankfull discharge and as a threshold in other studies (Cheng et al., 2013; Xu et al., 2017). A standard frequency analysis on annual high flows was performed for each tributary to assess the two-year return period flow (Q2), using a lognormal distribution.

For a given year, all the daily flows greater than the Q2 were analyzed to see whether the presence of wetlands had an attenuation or amplification effect. Figure 6.3(a) illustrates a theoretical probability of exceedance of a Q2 with respect to the flow duration curve of all daily flows of a given year (not the flow duration curve of the annual maximum flows over several years). Thus, if the daily flow was higher than or equal to the 2-year return flow (1950-2013), it was considered as a flood event depicted in time beginning when the flow exceeded the threshold and ending when flow recessed below the threshold (Figure 6.3(b)). Flood duration was defined as the number of consecutive days of flooding in the event. Peak flow was defined as the maximum flow during the event. Mean flow was defined as the average daily flow during the event. Rising and falling limbs referred to the rise and fall of flows during the flood event, respectively. To clarify the potential for flooding, flood events lasting at least five days were extracted (Figure 6.3(b)). Simultaneously, the mean flow, duration and flow volume for the rising and falling limbs of the hydrograph were determined (Figure 6.3(c)).

Finally, the differences in the values of the selected indicators between simulations with and without wetlands were calculated (Wu et al., 2020). Results related to flow or volume are presented as runoff (ratio of volume/subwatershed area). To complete the analysis, the occurrence of beneficial services (i.e., how often over the series of flood events the wetlands provided positive services such as high flow attenuation) was determined.



(Figure taken without the permission of the publisher from Wu et al., 2020)

Figure 6-3. Methodological framework used to (a) define for a given year event flows greater than a given threshold (ex.: Q2), (b) extract and (c) characterize flood events.

Table 6.3 summarizes the impact of wetlands on high flow events, showing the magnitude attenuation of peak flow, flow duration, mean flow, and runoff volume. Negative values in the table indicate attenuation.

Table 6.4 presents the relative occurrence rate of attenuation (that is, the occurrence rate of negative values for the selected indicators).

Table 6.3 clearly indicates that median values for peak flow, mean flow and volume are mostly reduced by existing wetlands for all subwatersheds except for the rising limb volume indicator for Lewis Creek and the falling limb of Ausable and Bouquet. Magnitude of reductions is related to the importance of the wetlands and drainage areas. The flow and volume attenuation are less important at a larger scale for the Lake Champlain NBS and Richelieu River. Attenuation is less important on the high flow event duration where subwatershed median duration in days indicates attenuation (negative value), no effects or even amplification (positive value).

Table 6.4 shows similar tendencies with important occurrence of flow and volume attenuation. Occurrence of attenuation on high flow event duration is less important, but small occurrence percentage does not correspond to high amplification percentage, as no impact (0 day variation) neither leads to attenuation nor to amplification.

For the 1950-2013 climate conditions, these results clearly illustrate the need to protect wetlands. Moreover, they clearly highlight the flow regulation services provided by the current distribution of wetlands in the LCRR watershed.

6.3 EFFECT OF CURRENT WETLANDS ON THE 2011 FLOOD

In addition to assessing the overall attenuation provided by wetlands, the study assessed the potential impacts that might have occurred during the 2011 flood had the wetlands not existed. Figure 6.4 presents the simulated 2011 hydrographs for both the reference (existing) condition, and without the presence of wetlands. The results are presented using a daily time step based on simulated HYDROTEL NBSs and HYDROTEL-WBM. The results include impacts on flows and water levels.

As reported in Table 6.5, had the existing wetlands not been present in 2011, flooding conditions would have been worse than those actually experienced. This substantiates the motivation behind efforts to conserve and protect existing wetlands.

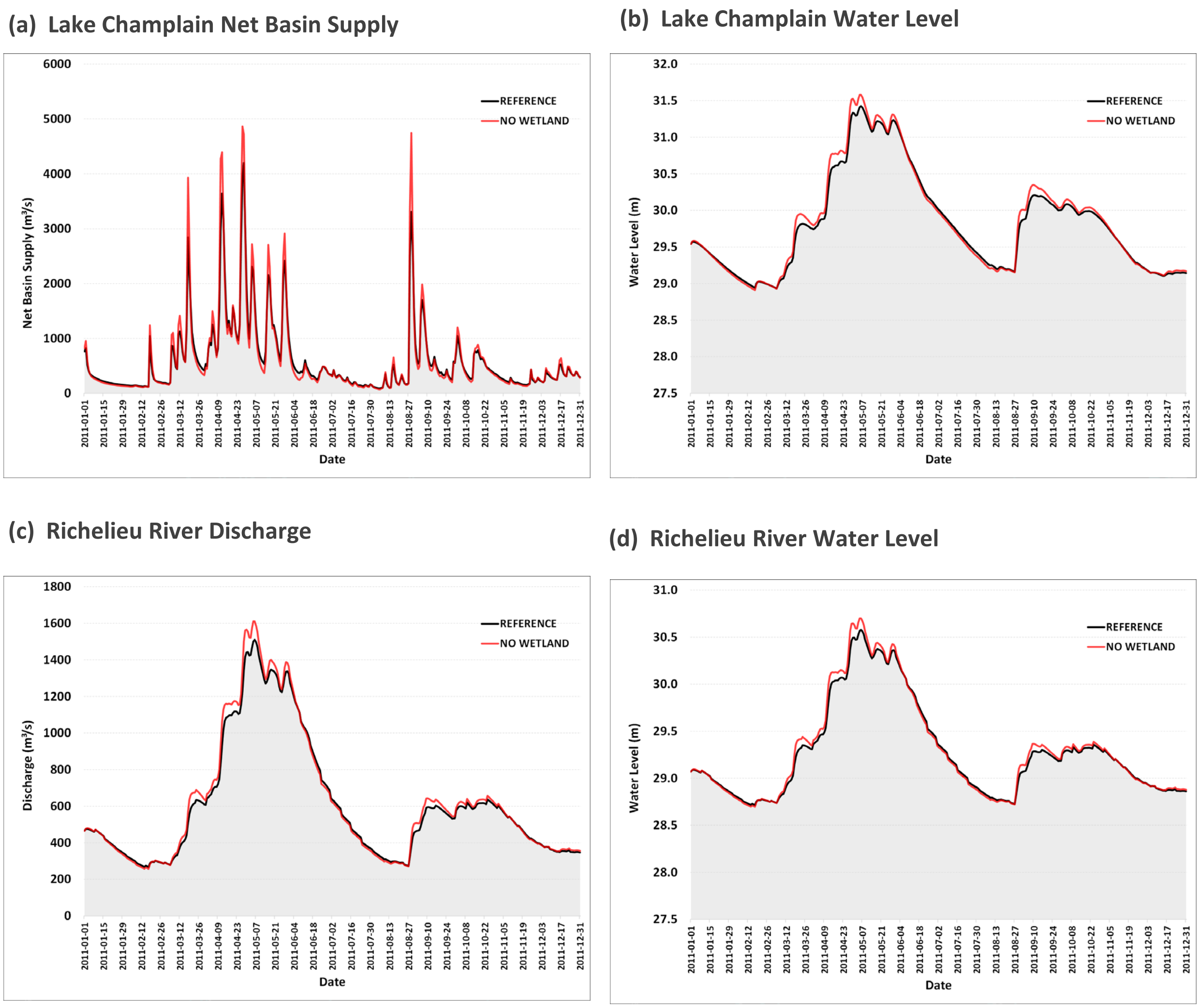
Table 6-3. Median values of wetland impact on peak flow, flow duration, mean flow, and flow volume (i.e., runoff volume).

#	WATERSHED	Peak flow (mm)	Duration (d)	Duration D1 (d)	Duration D2 (d)	Mean flow (mm)	Mean flow D1 (mm)	Mean flow D2 (mm)	Volume (mm)	Volume D1 (mm)	Volume D2 (mm)
1	Great Chazy	-6.5	-1	-1	0	-3.0	-3.5	-2.3	-30.6	-29.5	-6.3
2	Little Chazy	-10.7	-2	-1	-1	-6.3	-6.5	-7.4	-56.3	-39.5	-13.8
3	Dead Creek	-10.6	1	1	0	-5.2	-8.0	-3.1	-21.3	-11.8	-10.3
4	Saranac	-3.1	-1	0	-1	-1.7	-2.4	-1.3	-19.3	-7.4	-11.9
5	Salmon	-5.5	0	0	0	-2.3	-2.6	-2.8	-18.8	-18.9	-1.4
6	Little Ausable	-5.2	1	0	0	-3.8	-4.8	-2.2	-9.0	-8.9	-3.3
7	Ausable	-3.9	0	0	1	-2.6	-2.8	-2.0	-11.9	-16.4	6.4
8	Bouquet	-4.4	1	0	1	-2.7	-2.7	-0.8	-6.9	-7.7	17.3
9	Putnam Creek	-7.8	0	0	0	-5.9	-7.6	-3.2	-25.9	-22.3	-15.9
10	La Chute	-0.4	-2	0	-1	-0.1	-0.2	-0.1	-8.7	-3.0	-6.9
11	Poultney	-7.2	0	0	0	-3.0	-3.3	-1.6	-17.2	-11.5	-3.2
12	Otter Creek	-1.8	-1	0	-1	-0.7	-0.8	-0.7	-16.9	-4.9	-8.7
13	Little Otter Creek	-17.3	1	0	1	-10.2	-14.4	-7.3	-20.1	-24.1	-5.6
14	Lewis Creek	-6.1	1	1	1	-3.7	-3.1	-4.4	-2.1	3.8	-5.9
15	LaPlatte	-5.0	-4	-3	-1	-0.4	-0.5	-4.7	-52.6	-47.9	-4.7
16	Winooski	-1.1	0	0	0	-0.7	-1.2	-0.4	-3.9	-2.5	-1.4
17	Lamoille	-2.7	-1	-1	0	-0.9	-1.3	-0.3	-17.2	-19.0	-0.5
18	Missisquoi	-3.2	-1	-1	0	-3.6	-4.7	-0.2	-26.0	-23.9	-0.2
19	De La Roche	-9.3	0	-1	1	-5.9	-6.7	-5.4	-39.6	-38.8	-9.3
20	Aux Brochets	-4.6	0	0	0	-4.0	-3.7	-5.4	-24.8	-15.9	-8.9
	LC NBS	**-2.9**	**-1**	**0**	**0**	**-1.0**	**-1.2**	**-0.8**	**-18.3**	**-13.5**	**-0.4**
	RR (Fryers)	***-0.3***	***-2***	***-1***	***-3***	***-0.2***	***-0.2***	***-0.2***	***-13.9***	***-5.3***	***-10.3***

Notes: D1 and D2 refer to the rising limb and falling limb of an event hydrograph, respectively. Negative values indicate attenuation.

Table 6-4. Relative occurrence rate of attenuation effect (negative value in Table 6.3) of wetlands on peak flow, flow duration, mean flow, and flow volume.

#	WATERSHED	Peak flow (mm)	Duration (d)	Duration D1 (d)	Duration D2 (d)	Mean flow (mm)	Mean flow D1 (mm)	Mean flow D2 (mm)	Volume (mm)	Volume D1 (mm)	Volume D2 (mm)
1	Great Chazy	100%	58%	58%	42%	100%	100%	92%	100%	83%	83%
2	Little Chazy	100%	64%	77%	55%	100%	100%	95%	100%	95%	77%
3	Dead Creek	100%	23%	23%	41%	100%	100%	95%	95%	68%	73%
4	Saranac	100%	58%	35%	65%	100%	100%	100%	96%	81%	96%
5	Salmon	100%	45%	45%	18%	100%	100%	82%	91%	73%	55%
6	Little Ausable	100%	0%	13%	0%	100%	100%	100%	100%	88%	63%
7	Ausable	100%	17%	33%	17%	100%	100%	67%	83%	83%	17%
8	Bouquet	100%	20%	20%	20%	100%	100%	100%	60%	100%	40%
9	Putnam Creek	100%	20%	20%	40%	100%	100%	100%	100%	80%	60%
10	La Chute	100%	75%	46%	71%	96%	79%	83%	100%	71%	92%
11	Poultney	100%	17%	33%	17%	100%	100%	67%	83%	83%	50%
12	Otter Creek	100%	79%	43%	57%	100%	86%	86%	100%	71%	100%
13	Little Otter Creek	100%	36%	36%	36%	100%	100%	100%	100%	100%	64%
14	Lewis Creek	100%	0%	0%	0%	100%	50%	100%	50%	0%	50%
15	LaPlatte	100%	100%	100%	50%	100%	100%	50%	100%	100%	50%
16	Winooski	100%	0%	0%	33%	100%	100%	67%	100%	67%	67%
17	Lamoille	100%	60%	80%	0%	100%	100%	80%	100%	100%	60%
18	Missisquoi	100%	60%	60%	0%	100%	80%	80%	100%	100%	60%
19	De La Roche	100%	40%	50%	30%	100%	90%	100%	90%	90%	60%
20	Aux Brochets	100%	33%	33%	33%	100%	100%	100%	100%	100%	100%
	LC NBS	**100%**	**80%**	**40%**	**40%**	**100%**	**100%**	**100%**	**100%**	**80%**	**80%**
	RR (Fryers)	***100%***	***88%***	***59%***	***78%***	***100%***	***98%***	***98%***	***100%***	***73%***	***100%***



**Observations are displayed in black and simulations in red.*

Figure 6-4. Impact of an absence of wetlands on LCRR flows and water levels given the 2011 conditions using HYDROTEL and WBM at a daily time step.

Table 6-5. Summary of the impact of an absence of wetlands on NBS flows, LC water levels, discharges in the RR at Fryers Rapids and RR water levels (Saint-Jean Marina) given the 2011 conditions.

Wetlands	Lake Champlain Basin	Richelieu River (Fryers)
Area (km²)	21,254	22,055
Wetlands Area (km²)	1,551	1,616
Wetlands Drainage Area (km²)	7,749	7,902
HYDROTEL + WBM (daily time step)		
Increase of the highest peak (%)	15.8% (NBS)	6.7% (DISC.)
Increase of the highest water level	15 cm (0.49%)	12 cm (0.40%)

7 LEARNING FROM THE 2011 FLOOD

The 2011 flood can be used to identify potential wetland or flooded agricultural land scenarios that might reduce flooding. Flow measurements for the Richelieu River (Aux Rapides Fryers, Canadian Government Hydrometric Station number 02OJ007) can be used to estimate the amount of water that would need to be stored to reduce the 2011 peak flow by certain percentages and estimate the surface area of additional wetlands or flooded farmland required to store the water.

The 2011 flood can be represented by a polynomial equation whereby the integrals of measured flows or synthetic flood flows have identical volumes of water over a given time interval. This simplified representation of the 2011 flows at the Fryers Rapids station from April 1st to July 3rd is shown in Figure 7.1. The synthetic flood curve is then used to evaluate potential flow reductions. Figure 7.1 provides an illustration of the synthetic flood hydrograph and reductions in peak flows of 5%, 10% or 20%. Table 7.1 presents estimates of additional wetlands area that would be required to provide 5%, 10%, and 20% reduction in peak flows for the 2011 flood at two storage depths, 50 cm and 10 cm.

As presented in Table 7.1, reducing the 2011 peak flow at Fryers Rapids by 5% would require an additional 632 km^2 of wetlands with a holding capacity of 50 cm of water; this corresponds to increasing the surface area of wetlands by 39% in the watershed upstream of Fryers Rapids or by 41% in the LC watershed. Given the same water holding capacity, a 20% decrease in peak flow would require flooding 68% of existing farmland upstream of the Fryers Rapids station or 79% of the existing farmland area of the LC watershed.

Table 7.1 demonstrates that reducing the peak flow of the 2011 flood on the RR would require adding large areas of wetlands or flooding substantial farmland areas. Also, the water height to be stored would be determinant, as illustrated by the estimates of additional areas of either wetlands or flooded farmland, which quickly become unrealistic with a water holding capacity of only 10 cm. From a flood management perspective, this simple exercise provides an appreciation of the order of magnitude of the area required to store water. It cannot in any case be considered as a hydrological modelling exercise.

The next chapters of the report focus on the evaluation of two primary scenarios using HYDROTEL: riparian agricultural land water storage and wetland construction/restoration.

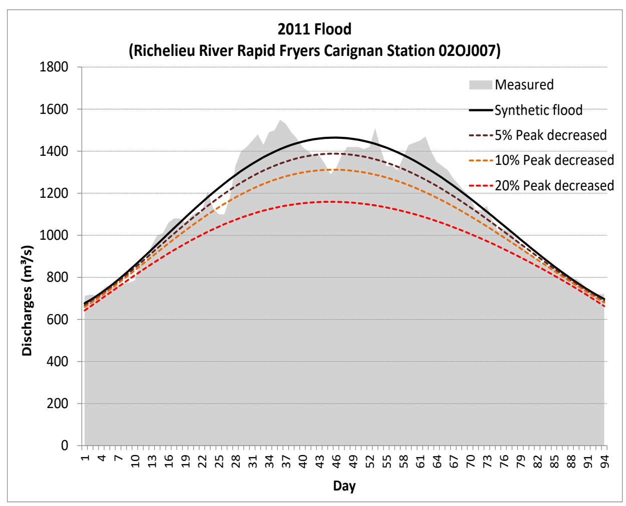


Figure 7-1. Simplified representations of the 2011 flood with a synthetic flood and ensuing shape of the flood given 5%, 10% and 20% reductions of the 2011 peak flow at the Fryers Rapids station from April 1st to July 3rd.

Table 7-1. Estimation of additional wetlands or flooded riparian farmland required to reduce the 2011 peak flow of the RR at Fryers Rapids, assuming the additional storage areas would either store 50 cm or 10 cm of water.

50-cm water height					
Peak Reduction Scenario	**Additional Wetlands (km²)**	**Percent Increase Over Existing Area**		**Percent of Existing Farmland Area Flooded**	
		Upstream Fryers	**LC Watershed**	**Upstream Fryers**	**LC Watershed**
5%	632	39%	41%	17%	20%
10%	1,263	78%	81%	34%	39%
20%	2,527	156%	163%	68%	79%
10-cm water height					
Peak Reduction Scenario	**Additional Wetlands (km²)**	**Percent Increase Over Existing Area**		**Percent of Existing Farmland Area Flooded**	
		Upstream Fryers	**LC Watershed**	**Upstream Fryers**	**LC Watershed**
5%	3,344	207%	216%	90%	104%
10%	6,688	414%	431%	181%	209%
20%	13,376	828%	862%	361%	418%

8 EVALUATION OF RIPARIAN AGRICULTURAL LANDSCAPES WATER STORAGE SCENARIO

The first alternative evaluated was the use of riparian agricultural landscapes for additional water storage. This scenario was produced to evaluate the additional benefits of flooding farmlands. This scenario evaluated these potential benefits by treating agricultural lands as if they were "wetlands", but without explicitly converting the farmland; rather, by mimicking the potential impact of storing water onto agricultural land close to the river network within a certain distance from each bank. In terms of modelling, the additional storage area was modelled using the isolated and riparian wetland modules provided by HYDROTEL and assigning parameter values to farmland that were equivalent to those of existing and dominant wetlands within each computational unit (RHHU) or average parameter values (see Appendix II) for RHHUs without existing wetlands.

This exploratory scenario was developed from a perspective of storing water on farmland located within a 1-km buffer zone along each bank of the river network. This led to an additional storage area of 2,471 km² in the Richelieu River watershed upstream of Fryers Rapids (from 1,616 km² to 4,087 km²) including 2,256 km² within the boundaries of the Lake Champlain watershed (from 1,551 km² to 3,807 km²). The 1-km buffer zone along the river network certainly represents an extensive area; the delineation of the buffer was meant to assess the effect of storing water on an extensive area of farmland, acknowledging that in all likelihood the actual buffer zone would be smaller. Further analyses could be done for a very large number of scenarios that are specifically designed for each sub watershed, but that was beyond the scope and schedule for this project. Figure 8.1 gives a general representation of the riparian agricultural landscapes water storage scenario.

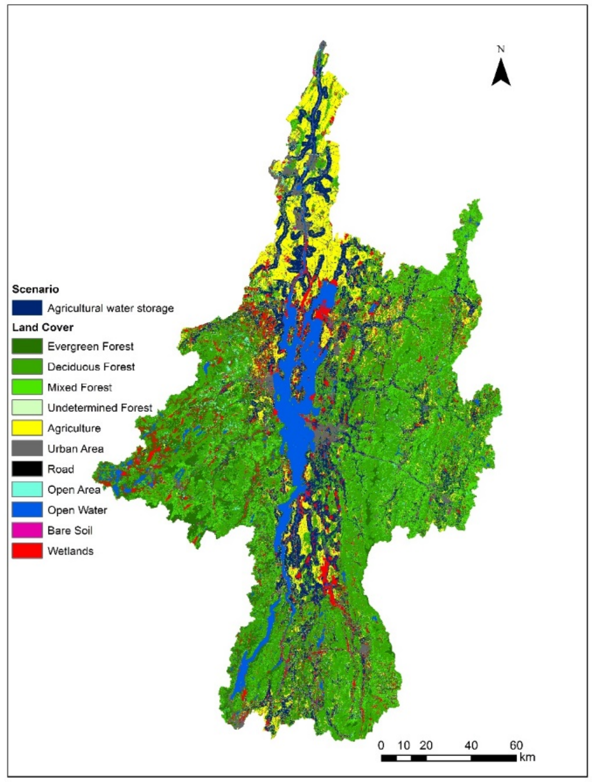


Figure 8-1. General representation of the riparian agricultural landscapes water storage scenario.

Table 8.1 describes for each subwatershed the impact of this water storage scenario on wetland and storage (i.e., farmland) areas, as well as on their respective drainage areas. A hydrological simulation for the 1950-2013 time period was performed using the additional storage area, and attenuation of high flows and amplification (a desirable effect) of low flows were quantified. The methodology is similar to the evaluation of the hydrological services provided by the current wetlands, except that this evaluation focused on the gains compared to the current situation.

Table 8-1. Spatial impact of storing water on riparian agricultural landscapes of the LCRR basin for the 20 LC subwatersheds, LC NBS and RR flows at Fryers Rapids.

#	WATERSHED	DRAINAGE (km²)	Wetlands+Storage		vs. Watershed		W Drainage		vs. Watershed	
			(km²)	GAIN (km²)*	(%)	GAIN (%)*	(km²)	GAIN (km²)	(%)	GAIN (%)
1	Great Chazy	778	212	105	27.2%	13.5%	357	-14	45.9%	-1.7%
2	Little Chazy	143	45	25	31.5%	17.3%	69	-4	48.4%	-2.5%
3	Dead Creek	114	47	20	41.3%	17.3%	51	-12	45.1%	-10.2%
4	Saranac	1579	201	18	12.8%	1.1%	763	3	48.3%	0.2%
5	Salmon	177	27	12	15.4%	7.1%	90	0	51.0%	-0.1%
6	Little Ausable	188	34	22	18.3%	11.6%	93	-2	49.4%	-0.9%
7	Ausable	1329	98	22	7.4%	1.7%	508	8	38.2%	0.6%
8	Bouquet	621	72	34	11.5%	5.5%	248	-7	39.9%	-1.2%
9	Putnam Creek	158	17	5	10.8%	3.3%	83	2	52.7%	1.3%
10	La Chute	678	34	9	5.0%	1.3%	187	12	27.5%	1.8%
11	Poultney	1778	373	253	21.0%	14.2%	779	5	43.8%	0.3%
12	Otter Creek	2446	572	348	23.4%	14.2%	958	-3	39.2%	-0.1%
13	Little Otter Creek	153	69	51	45.3%	33.5%	66	-14	43.1%	-8.9%
14	Lewis Creek	203	60	44	29.7%	21.8%	83	3	41.1%	1.4%
15	LaPlatte	118	50	43	42.7%	36.0%	47	3	39.4%	2.9%
16	Winooski	2756	273	194	9.9%	7.0%	868	210	31.5%	7.6%
17	Lamoille	1866	276	182	14.8%	9.8%	804	97	43.1%	5.2%
18	Missisquoi	2212	398	243	18.0%	11.0%	914	28	41.3%	1.3%
19	De La Roche	144	61	45	42.2%	31.6%	62	0	42.9%	-0.1%
20	Aux Brochets	664	224	168	33.8%	25.2%	250	32	37.6%	4.9%
	LC	**21254**	**3807**	**2256**	**17.9%**	**10.6%**	**8047**	**298**	**37.9%**	**1.4%**
	RR (Fryers)	**22055**	**4087**	**2471**	**18.5%**	**11.2%**	**8255**	**352**	**37.4%**	**1.6%**

**The gains mean an increase in storage area (for example, for Great Chazy with storing water on agricultural land, 27.2% (13.8% of wetland land cover + 13.5% flooded farmland) of the watershed is in storage area.*

The calculation procedure was as follows:

- For high flows:
$$\frac{Current\ Wetlands - Agricultural\ \ Scenario}{Current\ Wetlands}$$
where a positive result corresponds to an attenuation.

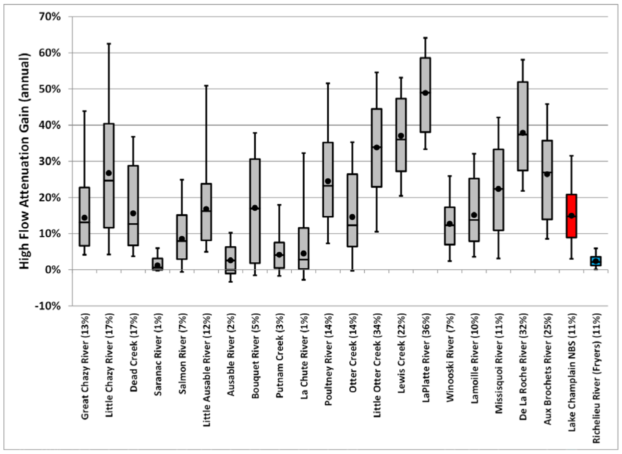
- For low flows:
$$\frac{Agricultural\ \ Scenario - Current\ Wetlands}{Current\ Wetlands}$$
where a positive result corresponds to an amplification.

8.1 EFFECT ON HIGH FLOWS

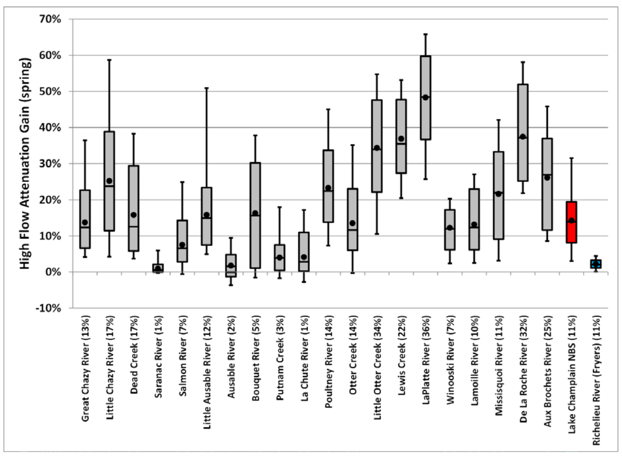
Figure 8.2 highlights the effects of the agricultural water storage scenario on the attenuation gain (a) on an annual basis, (b) for spring and (c) for summer/fall. As this study places emphasis specifically on high flows and flood risk, the effects of the agricultural water storage scenario on low flow gains are not discussed here; however, these results are reported in Appendix II (Figure A3.2). Table 8.2 summarizes the annual effect on the attenuation gain for (i) the 20 major LC subwatersheds, (ii) LC NBS, (iii) RR flows at Fryers Rapids and (iv) water levels of the LC and RR (at Marina Saint-Jean) based on the use of the NBS simulated by HYDROTEL as input to the daily Lake Champlain water balance model. Table 8.2 also includes the effects for specific flood years.

Logically, for subwatersheds with a high percentage gain of additional water storage area, a significantly higher impact on high flows is observed when compared to subwatersheds with smaller percentage gain. Figure 8.2 illustrates how the impacts vary from year to year in each subwatershed. The annual and spring attenuation gains are similar, since the highest flow occurs most of the time during spring. Figure 8.2 shows that for seven (7) subwatersheds (Saranac, Salmon, Ausable, Bouquet, Putnam Creek, La Chute and Otter Creek), the annual or spring results can have negative impacts (increase of high flows) and for nine (9) subwatersheds (Great Chazy River, Dead Creek, Saranac, Salmon, Little Ausable, Ausable, Bouquet, La Chute and Richelieu River (Fryers)), autumn results include negative impacts. Results demonstrate a clear and consistent effect of the relative impacts of wetlands on high flows. However, there are a few cases of negative impacts whereby singular conditions, that is antecedent soil moisture or water level conditions in wetlands can be detrimental. Such negative values suggest that for a particular year, storing water on agricultural land could worsen the high flows. However, it is important to also note that all median or average attenuation gains are positive.

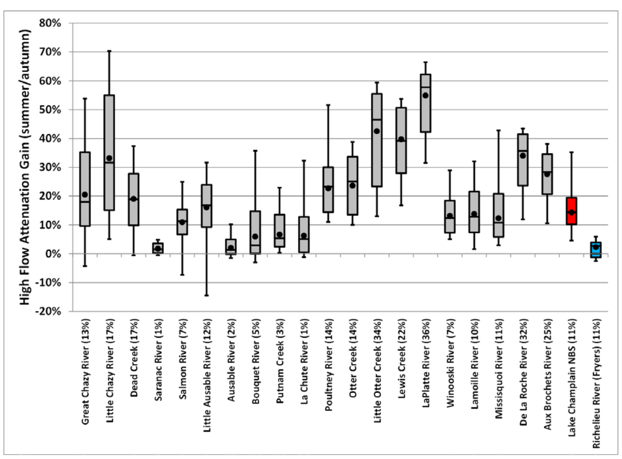
Table 8.2 indicates variable maximum or minimum year impacts for all the modelling period and clear contribution of agricultural water storage for specific noticeable flood years (1973, 1983, 1984, 2011, and 2013). Negative impact can occur when initial water conditions in wetlands and temporality of flooding can increase high flow, but the relative high flow increases are small and limited. Based on the 1950-2013 meteorological conditions, large-scale storing of water on riparian agricultural landscapes can provide relief by reducing peak flows. Indeed, when compared to current conditions, increasing the water storage area from 7.3% to 17.9% of the LC basin area could induce a decrease at the daily time step of the highest NBS peak flows by 15% on average, and the peak flow at the Fryers Rapids on the Richelieu River (RR) by 2% on average. Such reductions are seen on Lake Champlain and Richelieu River water levels as well (on average, 4 cm on the LC and 3 cm at the St-Jean-sur-le-Richelieu marina). Thus, on a daily time scale, large-scale storing of water on riparian agricultural landscapes could prove to provide a valuable mitigation measure.



(a) (Min; Max; 10th percentile; 90th percentile; Median; Average)



(b) (Min; Max; 10th percentile; 90th percentile; Median; Average)



(c) (Min; Max; 10th percentile; 90th percentile; Median; Average)

Figure 8-2. Gain in high flow attenuation due to storing water on riparian agricultural landscapes of the LCRR basin for the 20 LC subwatersheds, LC NBS and RR flows at Fryers Rapids with respect to current conditions for various temporal scales: (a) annual, (b) spring and (c) summer/fall.

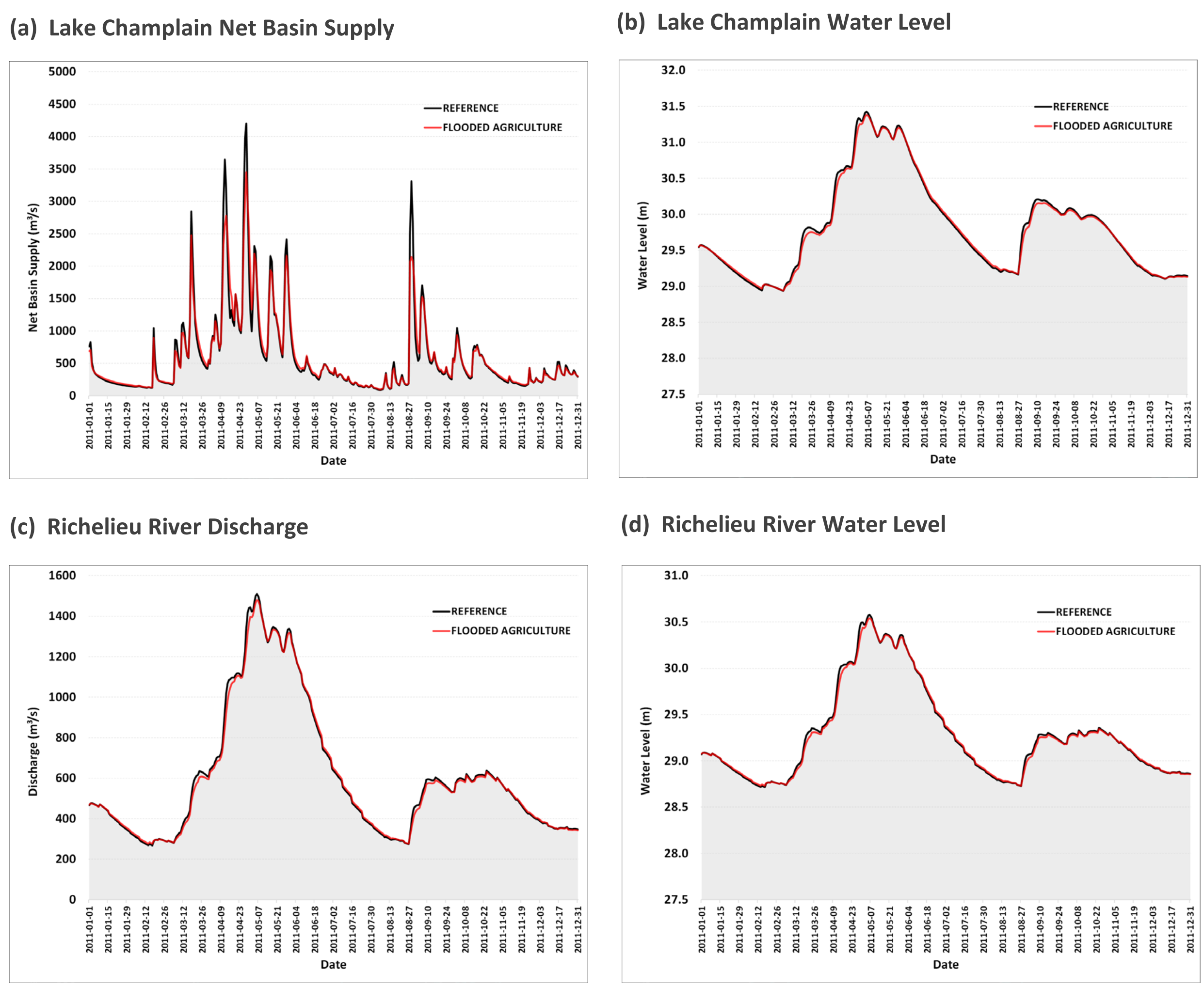
Table 8-2. Gain in annual high flow attenuation when storing water on riparian agricultural landscapes of the LCRR basin for the 20 LC subwatersheds, LC NBS, RR flows at Fryers Rapids and LC and RR (Saint-Jean Marina) compared to current conditions.

#	WATERSHED (WT GAIN %)	MIN		MAX		FLOODED YEAR					AVERAGE	MEDIAN
		YEAR	ATTENUATION	YEAR	ATTENUATION	1973	1983	1984	2011	2013		
1	Great Chazy (13%)	1983	4.2%	1996	43.9%	10.1%	4.2%	9.2%	36.5%	32.9%	14%	13%
2	Little Chazy (17%)	1964	4.2%	1957	62.5%	22.4%	16.9%	29.0%	57.2%	48.4%	27%	25%
3	Dead Creek (17%)	2007	3.7%	1965	36.8%	4.7%	16.4%	11.7%	11.3%	11.6%	16%	13%
4	Saranac (1%)	1959	-0.2%	2003	6.0%	2.4%	4.0%	1.1%	0.3%	4.1%	1%	1%
5	Salmon (7%)	1969	-0.6%	1998	24.9%	6.3%	11.7%	6.3%	14.4%	16.2%	9%	8%
6	Little Ausable (12%)	1954	4.9%	1987	50.9%	7.8%	16.8%	15.5%	24.9%	23.9%	17%	16%
7	Ausable (2%)	1974	-3.3%	2004	10.2%	0.4%	0.2%	5.8%	1.1%	3.9%	3%	3%
8	Bouquet (5%)	1999	-1.5%	1982	37.9%	28.1%	18.0%	26.1%	27.1%	6.2%	17%	17%
9	Putnam Creek (3%)	1974	-1.7%	1977	18.0%	1.4%	4.1%	9.6%	6.4%	7.4%	4%	4%
10	La Chute (1%)	1963	-2.7%	1957	32.3%	1.9%	0.9%	4.7%	6.8%	1.6%	5%	3%
11	Poultney (14%)	1967	7.3%	2011	51.6%	28.0%	16.8%	41.1%	51.6%	23.7%	24%	23%
12	Otter Creek (14%)	1991	-0.2%	1965	35.3%	13.2%	9.1%	13.9%	25.1%	10.7%	15%	12%
13	Little Otter Creek (34%)	1983	10.6%	2012	54.6%	34.1%	10.6%	29.4%	37.7%	33.4%	34%	34%
14	Lewis Creek (22%)	1967	20.5%	1998	53.1%	37.2%	27.6%	33.6%	39.2%	40.9%	37%	36%
15	LaPlatte (36%)	2005	33.3%	1980	64.1%	45.1%	35.9%	43.1%	50.2%	49.2%	49%	49%
16	Winooski (7%)	1961	2.4%	2011	25.9%	17.7%	8.7%	17.3%	25.9%	11.9%	13%	12%
17	Lamoille (10%)	1980	3.6%	2010	32.1%	25.9%	15.0%	16.3%	22.0%	27.1%	15%	14%
18	Missisquoi (11%)	1980	3.1%	1982	42.1%	15.8%	12.8%	9.0%	27.8%	25.8%	22%	22%
19	De La Roche (32%)	1971	21.8%	1977	58.1%	45.5%	32.4%	40.0%	30.2%	33.6%	38%	37%
20	Aux Brochets (25%)	1992	8.6%	1982	45.8%	31.1%	28.7%	34.5%	30.2%	36.1%	26%	27%
	LC NBS (11%)	**1980**	**3.0%**	**1982**	**31.6%**	**15.0%**	**11.3%**	**19.4%**	**17.9%**	**21.7%**	**15%**	**15%**
	RR (Fryers) (11%)	***1975***	***0.1%***	***1957***	***5.9%***	***1.7%***	***2.0%***	***3.3%***	***2.0%***	***2.5%***	***2%***	***2%***
	LC Water Level (cm)	***1985***	***0***	***1998***	***10***	***5***	***4***	***6***	***5***	***5***	***4***	***4***
	RR Water Level (cm)	***1975***	***0***	***1998***	***7***	***2***	***3***	***4***	***4***	***3***	***3***	***3***

8.2 EFFECT ON THE 2011 FLOOD

This section focuses on 2011 hydrographs at various spatial scales, comparing simulation results related to the current effect of wetlands and the water storage scenario on riparian agricultural landscapes. Here the results are presented at a daily time step in terms of the NBS simulated by HYDROTEL and flows and water levels supplied by the daily WBM using the aforementioned NBSs as inputs.

Figure 8.3 shows the impact of water storage on riparian agricultural landscapes of the LCRR basin on NBS flows (a), LC water level (b), discharge in the RR at the Fryers Rapids (c) and RR water level (Saint-Jean Marina) (d) for the 2011 conditions. Table 8.3 summarizes the effect of the agricultural land water storage scenario given the 2011 conditions.



**Observations are displayed in black and simulations in red.*

Figure 8-3. Figure 8.3 Impact of water storage on riparian agricultural landscapes of the LCRR basin given the 2011 conditions using HYDROTEL and WBM at a daily time step.

Table 8-3. Summary of the effect of water storage on riparian agricultural landscape on NBS flows, LC water levels, discharges in the RR at the Fryers Rapids and RR water levels (Saint-Jean Marina) given the 2011 conditions.

Wetlands	Lake Champlain Basin	Richelieu River (Fryer)
Area (km²)	21,254	22,055
Wetlands Area + Storage Area (km²)	3,807 (1,551)	4,087 (1,616)
Wetlands Drainage Area (km²)	8,047 (7,749)	8,255 (7,902)
HYDROTEL + WBM (daily time step)		
Decrease of the highest peak (%)	-17.9% (NBS)	-2.0% (DISC.)
Decrease of the highest water level	-5 cm (-0.14%)	-4 cm (-0.12%)

() indicates existing wetland area or relative water level decrease

Extending the water storage area to riparian agricultural landscape was conducive to reducing Lake Champlain NBS peak flows by 17.9%; decreasing the lake water levels accordingly by 5 cm. The benefits are not in the same proportion for the Richelieu River discharges (-2.0%), but the water level reduction is consistent (- 4 cm). Thus, on a daily time scale, large-scale storing of water on riparian agricultural landscapes could have provided significant relief in 2011. It remains important to note that this scenario includes considerable additional storage area and would be challenging to implement. Allowing water to be stored on more than 2,250 km^2 of riparian agricultural landscape would require extensive work and take a long time to implement.

9 WETLANDS CONSTRUCTION/ RESTORATION SCENARIOS

9.1 WETLANDS CONSTRUCTION/ RESTORATION SCENARIO BASED ON SPATIAL DATA

This study developed wetland construction/restoration scenarios based on readily available spatial data. This approach is based on two specific spatial components: the digital elevation model (DEM) and the land cover map.

The approach is summarized in Figure 9.1 and can be described as follows:

1. Location of depressions (a.k.a. pits) in the DEM (labeled letter B in the left frame of Figure 9.1).

2. Using the flow matrix, identification of the converging cells towards the pit. Those cells adjacent to the pit represent the level one (1) depression capacity (numbered 1 in the left frame of Figure 9.1).

3. Building the depression capacity level by level. Cells adjacent and converging to level one (1) cells represent level two (2); repeating this process allows for the delineation of all potential depression areas of the DEM (numbered 1 to 10 in the left frame of Figure 9.1).

4. Identification of various depressions with different design criteria (e.g., threshold level for storage capacity, wetland area represented by the number of cells converging towards the deepest cell, (shown in green on the left frame of Figure 9.1) and drainage/contributing area, (blue cells on Figure 9.1) representing cells converging towards the wetland area.

5. Wetland scenarios consider a few land cover classes (forest, agricultural land), thus excluding existing wetlands, urban areas and roads.

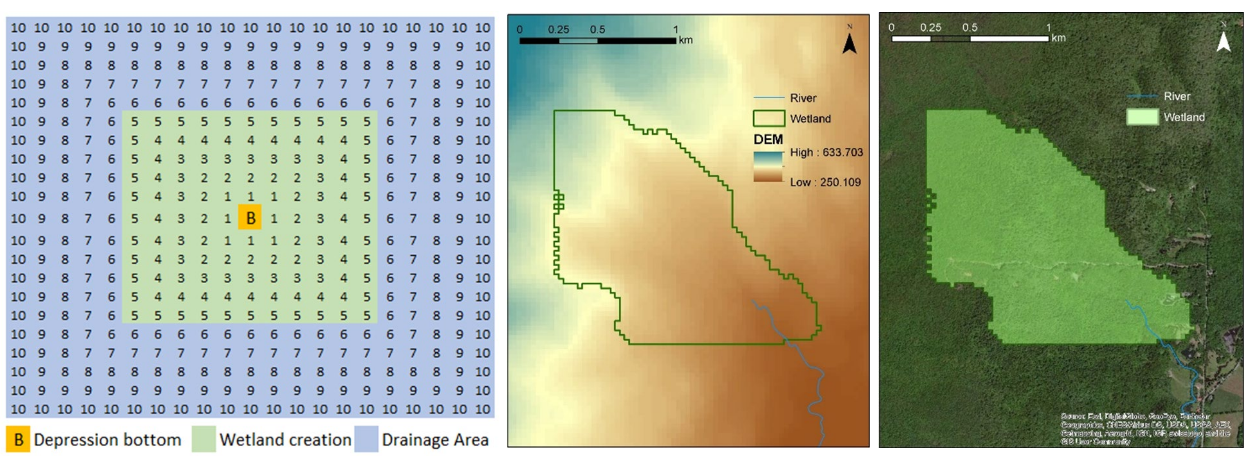


Figure 9-1. Development of a wetland scenario using a DEM and a few design criteria (e.g., wetland area or number of cells converging towards the deepest tile and drainage area or minimum number tiles converging towards the wetland area).

Figure 9.1 presents the development and location of a new wetland based on the DEM (middle image) and the ensuing display on satellite view of the terrain (right image).

Using this approach, a conservative wetland construction/restoration scenario was developed and the associated added value was evaluated. The estimation made in Chapter 7 indicated that addition of 632 km^2 of wetlands with a 50-cm water height is needed to reduce the 2011 peak flow at Fryers Rapids by 5%. Based on this estimate, a scenario was developed corresponding to the addition of 649 km^2 of wetlands in the Richelieu River watershed upstream of the Fryers Rapids point, including 647 km^2 in the Lake Champlain watershed). Figure 9.2 illustrates a general representation of this scenario.

9.1.1 Effect on high flows

Table 9.1 describes the impact of adding 652 km^2 of wetlands on the LCRR wetland area and wetland drainage area. For this scenario, a hydrological simulation was performed using the 1950-2013 time intervals. The gains in high flow attenuation or low flow amplification were assessed through a comparison between the high flow attenuation and low flow amplification associated with this scenario and those achieved by current wetlands distribution within the LCRR watershed. The methodology was thus similar to that used in Chapter 8; that is, the calculation procedure was as follows:

- For high flows:
  $$\frac{Current\ Wetlands - Wetland\ \ Scenario}{Current\ Wetlands}$$
  where a positive result corresponds to an attenuation.

- For low flows:
  $$\frac{Wetland\ \ Scenario - Current\ Wetlands}{Current\ Wetlands}$$
  where a positive result corresponds to an amplification.

Figure 9.3 highlights the impact (annual, spring, summer/autumn) of the wetland scenario on high flow attenuation. As this study places emphasis on high flow and flood risk, the impact of the wetland scenario on the gain in low flow amplification is not discussed here; however, these results are reported in Appendix III (Figure A3.3). Table 9.2 summarizes the annual impact of the wetland scenario on (i) the gains in high flow attenuation for the 20 major LC subwatersheds, (ii) LC NBS, (iii) RR flows at the Fryers Rapids and (iv) water levels in LC and RR (Marina Saint-Jean) using the previously described methodology; that is, based on HYDROTEL NBSs as input to the daily Lake Champlain WBM. Similarly, Table 9.2 includes the impacts with respect to specific flood years as well.

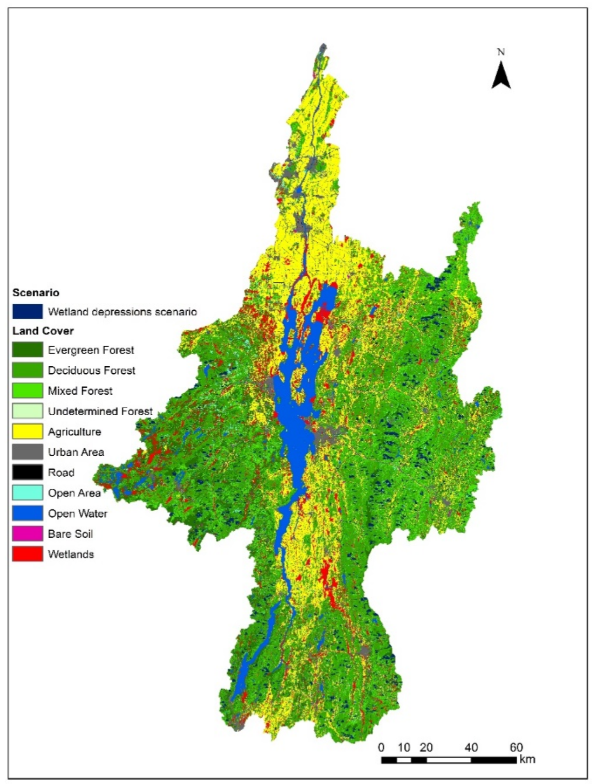


Figure 9-2. General representation of the wetland scenario using the DEM.wetland area).

Table 9-1. Spatial impact of the wetland scenario on the LCRR basin for the 20 LC subwatersheds, LC NBS and RR flows at Fryers Rapids.

#	WATERSHED	DRAINAGE (km²)	Wetlands		vs. Watershed		W Drainage		vs. Watershed	
			(km²)	GAIN (km²)*	(%)	GAIN (%)*	(km²)	GAIN (km²)	(%)	GAIN (%)
1	Great Chazy	778	112	5	14.4%	0.7%	376	6	48.4%	0.8%
2	Little Chazy	143	21	1	14.6%	0.4%	76	3	53.1%	2.2%
3	Dead Creek	114	28	0	24.2%	0.2%	64	1	56.5%	1.2%
4	Saranac	1579	220	36	13.9%	2.3%	780	19	49.4%	1.2%
5	Salmon	177	16	2	9.2%	0.9%	95	5	53.6%	2.6%
6	Little Ausable	188	17	4	8.8%	2.1%	103	8	54.8%	4.5%
7	Ausable	1329	133	57	10.0%	4.3%	558	58	42.0%	4.4%
8	Bouquet	621	64	27	10.4%	4.3%	284	28	45.7%	4.6%
9	Putnam Creek	158	14	2	8.9%	1.5%	83	2	52.5%	1.1%
10	La Chute	678	57	31	8.4%	4.6%	200	26	29.5%	3.8%
11	Poultney	1778	181	61	10.2%	3.4%	836	61	47.0%	3.5%
12	Otter Creek	2446	310	86	12.7%	3.5%	1092	130	44.6%	5.3%
13	Little Otter Creek	153	19	1	12.3%	0.6%	80	0	52.1%	0.2%
14	Lewis Creek	203	20	4	10.0%	2.1%	89	8	43.8%	4.2%
15	LaPlatte	118	9	1	7.8%	1.1%	48	5	40.9%	4.5%
16	Winooski	2756	231	152	8.4%	5.5%	882	224	32.0%	8.1%
17	Lamoille	1866	153	59	8.2%	3.1%	804	97	43.1%	5.2%
18	Missisquoi	2212	243	89	11.0%	4.0%	994	108	44.9%	4.9%
19	De La Roche	144	16	0	11.0%	0.3%	64	2	44.2%	1.2%
20	Aux Brochets	664	63	6	9.4%	0.9%	239	21	35.9%	3.1%
	LC	**21254**	**2199**	**647**	**10.3%**	**3.0%**	**8595**	**846**	**40.4%**	**4.0%**
	RR (Fryers)	**22055**	**2265**	**649**	**10.3%**	**2.9%**	**8768**	**865**	**39.8%**	**3.9%**

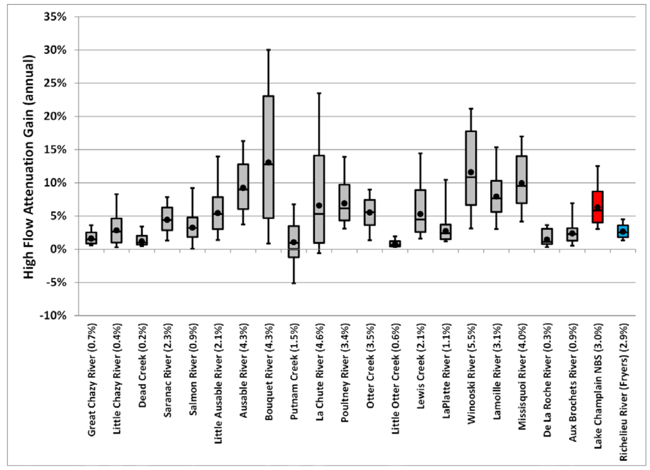
**The gains mean the increase in wetland area (for example, for Great Chazy with the addition of wetlands, 14.4% (13.8% of wetland land cover + 0.7% of additional wetland) of the watershed is in wetland area.*

For subwatersheds with a high percentage gain of additional wetlands, a proportional effect on high flows was observed, when compared to subwatersheds with smaller increase in wetland area. Figure 9.3 shows how the impacts vary from year to year in each subwatershed. The annual and spring attenuation gains are similar since the highest flow occurs most of the time during spring.

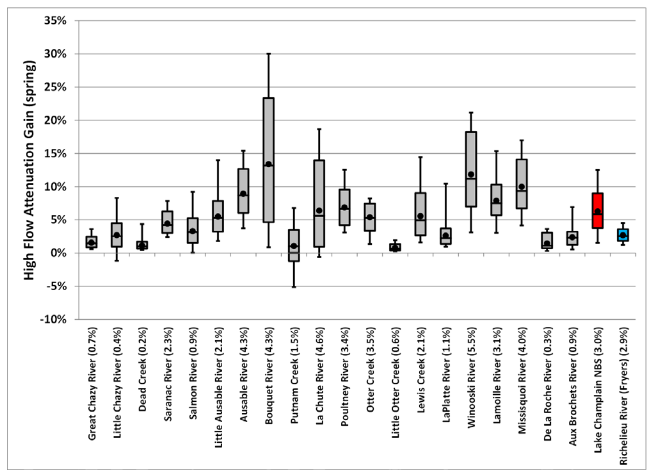
Figure 9.3 shows that for three (3) subwatersheds (Little Chazy River, Putnam Creek and La Chute), annual or spring results include negative impacts (increase of high flows), and for seven (7) subwatersheds (Saranac, Salmon, Little Ausable, Putnam Creek, La Chute River, Little Otter Creek and Richelieu River (Fryers)), autumn results include negative impacts. Such negative values suggest that, for certain years, additional wetlands could worsen the high flows. However, it is important to note that all median or average attenuation gain results are positive.

Table 9.2 indicates variable maximum or minimum year impacts for all the modelled period and clear contribution of additional wetlands for specific noticeable flood years (1973, 1983, 1984, 2011, and 2013). Based on the 1950-2013 meteorological conditions, increasing wetland area can reduce peak flows. Indeed, increasing the wetland area from 7.3% to 10.3% of the LC basin area could induce a decrease at the daily time step of the highest NBS peak flows by 6.3% on average; and the peak flow at Fryers Rapids on the Richelieu River (RR) by 2.6% on average.

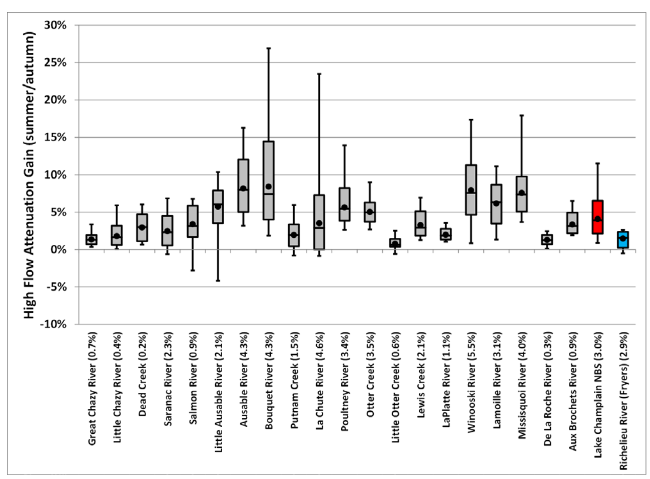
Such reductions are also seen on the water levels of Lake Champlain and Richelieu River (on average, 5 cm on LC and 3 cm at the St-Jean-sur-le-Richelieu marina). Thus, given the results obtained from this hydrological modelling exercise using a daily time step, increasing the wetland area by 3% could prove to provide a valuable mitigation measure.



(a) (Min; Max; 10th percentile; 90th percentile; Median; Average)



(b) (Min; Max; 10th percentile; 90th percentile; Median; Average)



(c) (Min; Max; 10th percentile; 90th percentile; Median; Average)

Figure 9-3. Gain in high flow attenuation gain when adding 649 km² of wetland in the LCRR basin for the 20 LC subwatersheds, LC NBS and RR flows at Fryers Rapids compare to current conditions for various temporal scales: (a) annual, (b) spring and (c) summer/fall.

Table 9-2. Gain in annual high flow attenuation when adding 649 km^2 of wetland in the LCRR basin for the 20 LC subwatersheds, LC NBS, RR flows at Fryers Rapids and LC and RR (Saint-Jean Marina) compared to current conditions.

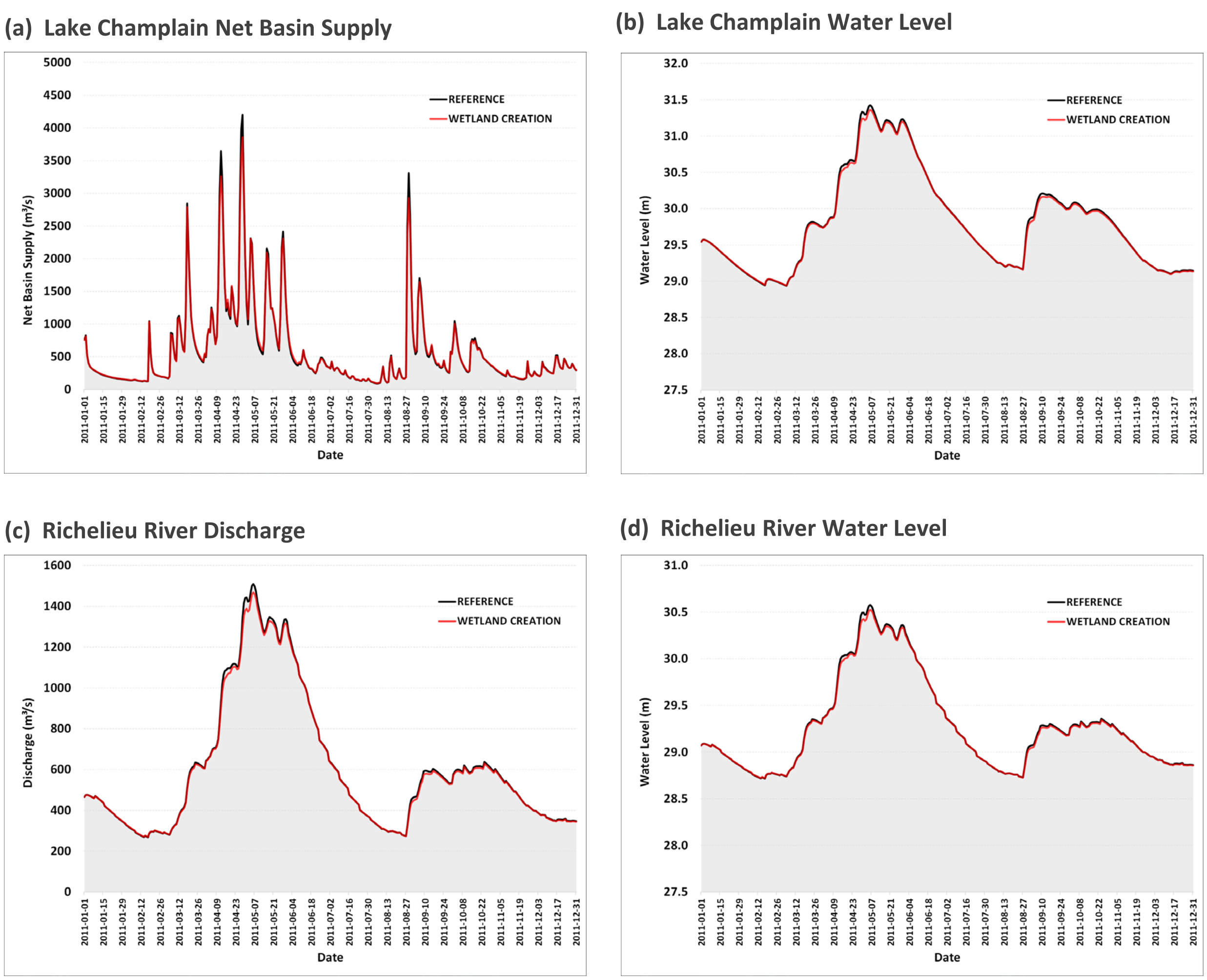
#	WATERSHED (WT GAIN %)	MIN		MAX		FLOODED YEAR					AVERAGE	MEDIAN
		YEAR	ATTENUATION	YEAR	ATTENUATION	1973	1983	1984	2011	2013		
1	Great Chazy (0.7%)	1961	0.6%	2013	3.6%	1.6%	1.1%	1.7%	2.5%	3.6%	1.6%	1.5%
2	Little Chazy (0.4%)	1967	0.3%	2013	8.3%	2.5%	3.3%	1.9%	4.5%	8.3%	2.8%	2.7%
3	Dead Creek (0.2%)	1969	0.5%	1995	3.4%	0.6%	0.9%	0.9%	0.7%	0.8%	1.2%	1.0%
4	Saranac River (2.3%)	1965	1.3%	1998	7.8%	3.9%	3.1%	3.2%	5.5%	4.9%	4.4%	4.4%
5	Salmon (0.9%)	1994	0.0%	1998	9.2%	3.3%	2.9%	4.0%	3.4%	5.9%	3.3%	3.2%
6	Little Ausable (2.1%)	2003	1.4%	1998	14.0%	3.8%	3.1%	5.3%	6.7%	4.3%	5.4%	5.3%
7	Ausable (4.3%)	1965	3.7%	1996	16.3%	10.7%	5.7%	11.3%	10.0%	6.5%	9.2%	9.0%
8	Bouquet (4.3%)	1959	0.9%	2001	30.0%	13.1%	13.5%	15.7%	11.5%	5.4%	13.0%	12.8%
9	Putnam Creek (1.5%)	1970	-5.1%	1990	6.8%	4.2%	1.6%	0.7%	2.0%	2.0%	1.0%	1.0%
10	La Chute (4.6%)	1964	-0.6%	1957	23.5%	2.9%	2.3%	1.6%	8.4%	0.2%	6.6%	5.3%
11	Poultney (3.4%)	1966	3.1%	2011	13.9%	5.3%	6.0%	9.6%	13.9%	5.1%	6.9%	6.1%
12	Otter Creek (3.5%)	1997	1.4%	2011	9.0%	7.4%	2.8%	5.3%	9.0%	2.8%	5.5%	5.6%
13	Little Otter Creek (0.6%)	1980	0.3%	1998	1.9%	0.7%	0.4%	0.6%	0.7%	0.6%	0.7%	0.7%
14	Lewis Creek (2.1%)	2002	1.6%	1958	14.4%	4.9%	2.9%	4.1%	4.6%	3.7%	5.3%	4.5%
15	LaPlatte (1.1%)	1970	1.2%	1998	10.5%	2.4%	2.1%	1.9%	2.4%	3.3%	2.7%	2.4%
16	Winooski (5.5%)	1991	3.1%	1998	21.2%	6.8%	5.2%	10.0%	17.3%	7.6%	11.6%	10.8%
17	Lamoille (3.1%)	1966	3.0%	1982	15.3%	8.2%	5.5%	6.6%	10.3%	7.4%	7.9%	7.6%
18	Missisquoi (4.0%)	2000	4.2%	1990	17.0%	6.9%	7.0%	9.1%	13.9%	9.8%	9.9%	9.5%
19	De La Roche (0.3%)	1991	0.3%	1975	3.6%	1.5%	1.1%	1.0%	0.9%	1.0%	1.5%	1.1%
20	Aux Brochets (0.9%)	1972	0.5%	1982	6.9%	1.6%	2.2%	2.1%	2.0%	3.0%	2.4%	2.3%
	LC NBS (3.0%)	**1966**	**3.0%**	**1992**	**12.5%**	**5.8%**	**4.3%**	**6.4%**	**8.2%**	**6.5%**	**6.3%**	**5.8%**
	RR (Fryers) (2.9%)	***1966***	***1.3%***	***1998***	***4.5%***	***2.4%***	***1.9%***	***2.4%***	***2.7%***	***1.9%***	***2.6%***	***2.5%***
	LC Water Level (cm)	***2004***	***1***	***1998***	***11***	***5***	***4***	***4***	***6***	***3***	***5***	***4***
	RR Water Level (cm)	***1965***	***1***	***1998***	***8***	***4***	***3***	***3***	***5***	***2***	***3***	***3***

9.1.2 Effect of wetlands construction/restoration scenario reported on the 2011 flood

This section evaluates the 2011 hydrographs at various spatial scales, comparing simulation results related to the current effect of wetlands and those of this wetland construction/restoration scenario. Here the results are presented at a daily time step in terms of the NBSs simulated by HYDROTEL and flows and water levels supplied by the daily WBM using the aforementioned NBSs as input.

Figure 9.4 shows the impact of the wetlands creation/restoration scenario in the LCRR basin on NBS flows (a), LC water level (b), flows in the RR at the Fryers Rapids (c) and RR water level (Saint-Jean Marina) (d). Table 9.3 summarizes the results of the wetland scenario given the 2011 conditions.

Increasing water storage area by adding additional wetlands decreased Lake Champlain net basin supply peak flows, inducing a decrease in the lake water level. The damping impact of Lake Champlain limits the benefits on the Richelieu River peak discharges, but water level reductions are similar. Thus, such a scenario of wetlands creation could be a beneficial practice relevant at the scale of Lake Champlain.



**Observations are displayed in black and simulations in red.*

Figure 9-4. Impact of wetlands creation/restoration scenario in the LCRR basin given the 2011 conditions using HYDROTEL and WBM at a daily time step.

Table 9-3. Summary of the effects of the wetland scenario on NBS flows, LC water level, discharge in the RR at the Fryers Rapids and RR water level (Saint-Jean Marina) for the 2011 conditions.

Wetlands	Lake Champlain Basin	Richelieu River (Fryer)
Area (km²)	21,254	22,055
Wetlands Area (km²)	2,199 (1,551)	2,265 (1,616)
Wetlands Drainage Area (km²)	8,595 (7,749)	8,768 (7,902)
HYDROTEL + WBM (daily time step)		
Decrease of the highest peak (%)	-8.2% (NBS)	-2.7% (DISC.)
Decrease of the highest water level	-6cm (-0.20%)	-5cm (-0.17%)

() indicates existing wetland area or relative water level decrease

9.2 USEPA WETLAND SCENARIO

Beginning two centuries ago, many wetlands were turned into farm fields or urban areas, yet wetlands play an important role in removing water pollution, regulating water storage and flows, and providing habitat for wildlife. Wetland restoration could help restore these benefits. The EnviroAtlas Potential Wetland Areas (PWA) dataset of the United States Environmental Protection Agency (USEPA) shows the potential locations of additional wetland areas for Vermont and New York states at a 30-meter resolution. Potential wetlands were identified as areas naturally accumulating water due to topography and that historically had poorly or very poorly drained underlying soils. This dataset was produced by the USEPA to support research and online mapping activities related to the EnviroAtlas[3], which allows the user to interact with a web-based, easy-to-use, mapping application to view and analyze multiple ecosystem services for the contiguous United States. The dataset is available as downloadable data[4] or as an EnviroAtlas map service. Additional descriptive information about each attribute in this dataset can be found in its associated EnviroAtlas Fact Sheet[5]. For this project, the geographical locations of the wetland areas with the highest development potential were overlaid on the current land cover map to build a USEPA wetland scenario; including the addition of 865 km² of wetlands in the Lake Champlain basin.

[3] https://www.epa.gov/enviroatlas
[4] https://edg.epa.gov/data/Public/ORD/EnviroAtlas
[5] https://www.epa.gov/enviroatlas/enviroatlas-fact-sheets

Figure 9.5 gives a general presentation of the USEPA high potential wetland areas.

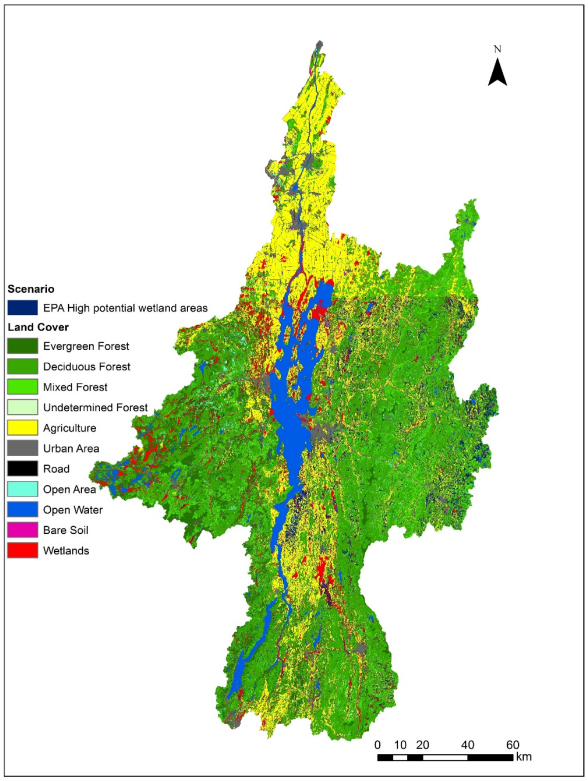


Figure 9-5. General representation of the USEPA high potential wetland area scenario.

9.2.1 Effect on high flows

Table 9.4 describes, for each subwatershed, the impact of the USEPA high potential wetland scenario on the LCRR wetland area and wetland drainage area. For this scenario, a hydrological simulation was performed using the 1950-2013 time interval. The gains in high flow attenuation or low flow amplification were assessed through a comparison between the high flow attenuation and low flow amplification associated with this scenario and those achieved by current wetlands distribution within the LCRR watershed. The methodology was thus similar to that used in Chapter 8.

The calculation procedure was as follows:

- For high flows:
  $$\frac{Current\ Wetlands - Wetland\ \ Scenario}{Current\ Wetlands}$$
  where a positive result corresponds to an attenuation.

- For low flows:
  $$\frac{Wetland\ \ Scenario - Current\ Wetlands}{Current\ Wetlands}$$
  where a positive result corresponds to an amplification.

Figure 9.6 highlights the impact (annual, spring, summer/autumn) of the USEPA high potential wetland scenario on high flow attenuation. As this study focuses on high flows and flood risk, the impacts of the USEPA high potential wetland scenario on low flow amplification gain are not discussed here; however, these results are reported in Appendix III (Figure A3.4). Table 9.4 summarizes the annual impact of the USEPA scenario on (i) the gains in high flow attenuation for the 20 major LC subwatersheds, (ii) LC NBS, (iii) RR flows at the Fryers Rapids and (iv) water levels in LC and RR (Marina Saint-Jean) using the previously described methodology that is based on HYDROTEL NBSs as input to the daily Lake Champlain WBM. Similarly, Table 9.5 includes the impacts with respect to specific flood years as well.

Table 9-4. Spatial impact of the EPA high potential wetlands scenario on the LCRR basin for the 20 LC subwatersheds, LC NBS and RR flows at Fryers Rapids.

#	WATERSHED	DRAINAGE (km^2)	Wetlands		vs. Watershed		W Drainage		vs. Watershed	
			(km^2)	GAIN (km^2)*	(%)	GAIN (%)*	(km^2)	GAIN (km^2)	(%)	GAIN (%)
1	Great Chazy	778	117	10	15.1%	1.3%	380	10	48.8%	1.2%
2	Little Chazy	143	23	2	15.8%	1.6%	74	1	51.7%	0.8%
3	Dead Creek	114	29	2	25.5%	1.5%	63	0	55.6%	0.3%
4	Saranac	1579	194	10	12.3%	0.6%	776	16	49.2%	1.0%
5	Salmon	177	17	2	9.5%	1.2%	91	0	51.2%	0.2%
6	Little Ausable	188	13	1	7.1%	0.5%	96	2	51.3%	1.0%
7	Ausable	1329	81	5	6.1%	0.3%	505	5	38.0%	0.4%
8	Bouquet	621	41	3	6.6%	0.5%	262	6	42.2%	1.0%
9	Putnam Creek	158	13	1	8.4%	0.9%	84	3	53.2%	1.8%
10	La Chute	678	29	4	4.3%	0.6%	187	13	27.6%	1.9%
11	Poultney	1778	142	22	8.0%	1.2%	807	32	45.4%	1.8%
12	Otter Creek	2446	346	122	14.2%	5.0%	1076	114	44.0%	4.7%
13	Little Otter Creek	153	32	14	20.8%	9.0%	88	9	57.6%	5.7%
14	Lewis Creek	203	32	17	16.0%	8.2%	96	15	47.2%	7.5%
15	LaPlatte	118	18	11	15.6%	8.9%	59	16	49.9%	13.4%
16	Winooski	2756	287	208	10.4%	7.6%	1030	371	37.4%	13.5%
17	Lamoille	1866	257	163	13.8%	8.7%	862	154	46.2%	8.3%
18	Missisquoi	2212	300	145	13.6%	6.6%	931	45	42.1%	2.0%
19	De La Roche	144	28	12	19.2%	8.6%	73	11	50.5%	7.5%
20	Aux Brochets	664	70	14	10.6%	2.1%	219	2	33.0%	0.3%
	LC	**21254**	**2416**	**865**	**11.4%**	**4.1%**	**8655**	**906**	**40.7%**	**4.3%**
	RR (Fryers)	**22055**	**2481**	**865**	**11.3%**	**3.9%**	**8810**	**907**	**39.9%**	**4.1%**

**The gains mean an increase in wetland area (for example, for Great Chazy with the addition of wetlands, 15.1% (13.8% of wetland land cover + 1.3% of additional wetlands) of the watershed is in wetland area.*

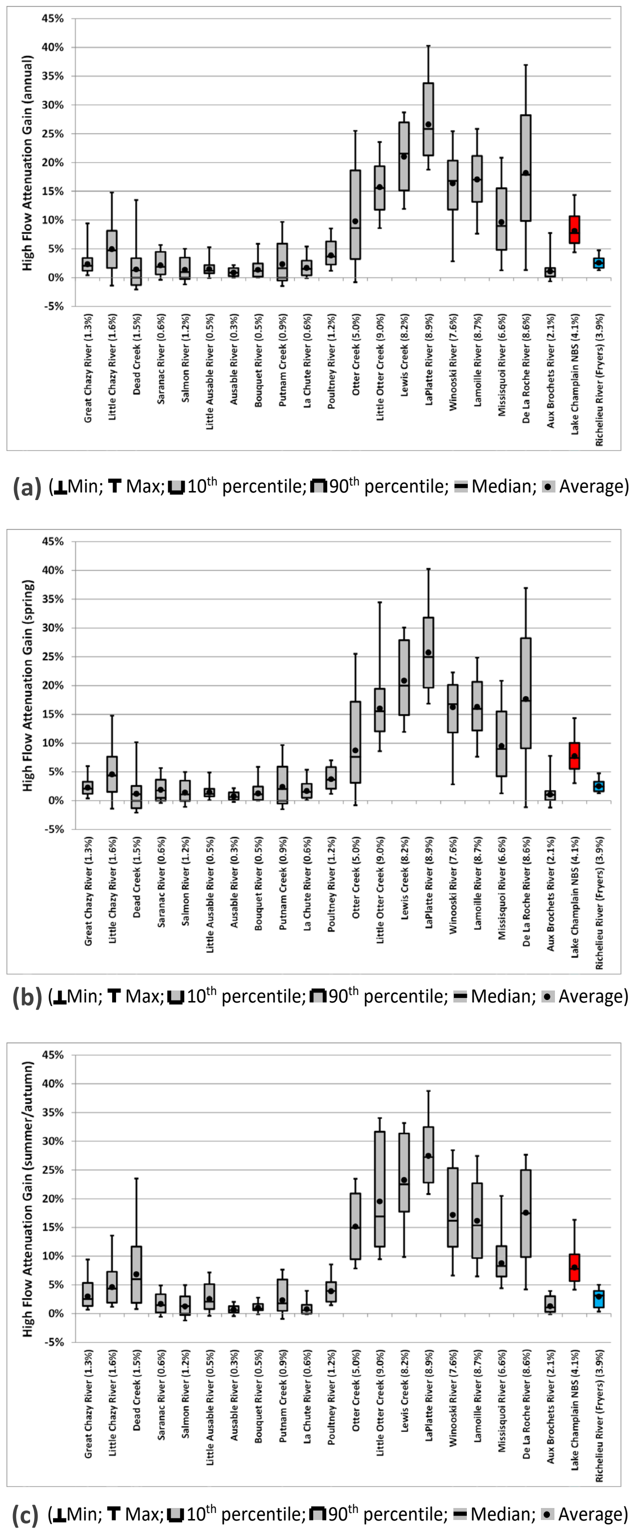


Figure 9-6. High flows attenuation gain of the EPA high potential wetlands scenario on the LCRR basin for the 20 LC subwatersheds, LC NBS and RR flows at Fryers Rapids compare to current conditions for various temporal scales: (a) annual, (b) spring and (c) summer/fall.

For this USEPA scenario, in subwatersheds with a high percentage gain of additional wetlands (mostly located in Vermont), a significantly higher impact on high flows was observed when compared to subwatersheds with smaller percentage gains. Figure 9.6 illustrates how the impacts vary from year to year in each subwatershed. The annual and spring attenuation gains are similar since the highest flow occurs most of the time during spring. Figure 9.6 shows that for ten (10) subwatersheds (Little Chazy, Dead Creek, Saranac, Salmon, Ausable, Putnam Creek, Otter Creek, De La Roche, Aux Brochets and La Chute) (mostly located in New York State), annual or spring results include negative impacts (increase of high flows), and for six (6) subwatersheds (Saranac, Salmon, Little Ausable, Putnam Creek, La Chute and Aux Brochets), autumn results include negative impacts. Negative impact can occur when initial water conditions in wetlands and temporality of flooding can increase high flow, but the relative high flow increases are small and limited. Such negative values suggest that for certain years, additional wetlands could worsen the high flows, but it is important to note that all median or average attenuation gains are positive.

Table 9.5 indicates variable maximum or minimum year impacts for all the modelled period and clear contribution of additional high potential wetlands for specific noticeable flood years (1973, 1983, 1984, 2011, and 2013). Based on the 1950-2013 meteorological conditions, adding high potential wetland area could also provide gains in reducing peak flows. Indeed, increasing the wetlands area from 7.3% to 11.4% of the LC basin area decreases the highest daily NBS peak flows by 8.1% on average and the peak flow at Fryers Rapids on the Richelieu River (RR) by 2.6% on average when compared to the current conditions. Such reductions are also observed on water levels of Lake Champlain and Richelieu River. These results demonstrate that the USEPA scenario could provide an effective flood mitigation, particularly for the state of Vermont.

Table 9-5. Gains in annual high flow attenuation of the USEPA high potential wetland scenario on the LCRR basin for the 20 LC subwatersheds, LC NBS, RR flows at Fryers Rapids and LC and RR (Saint-Jean Marina) compared to current conditions.

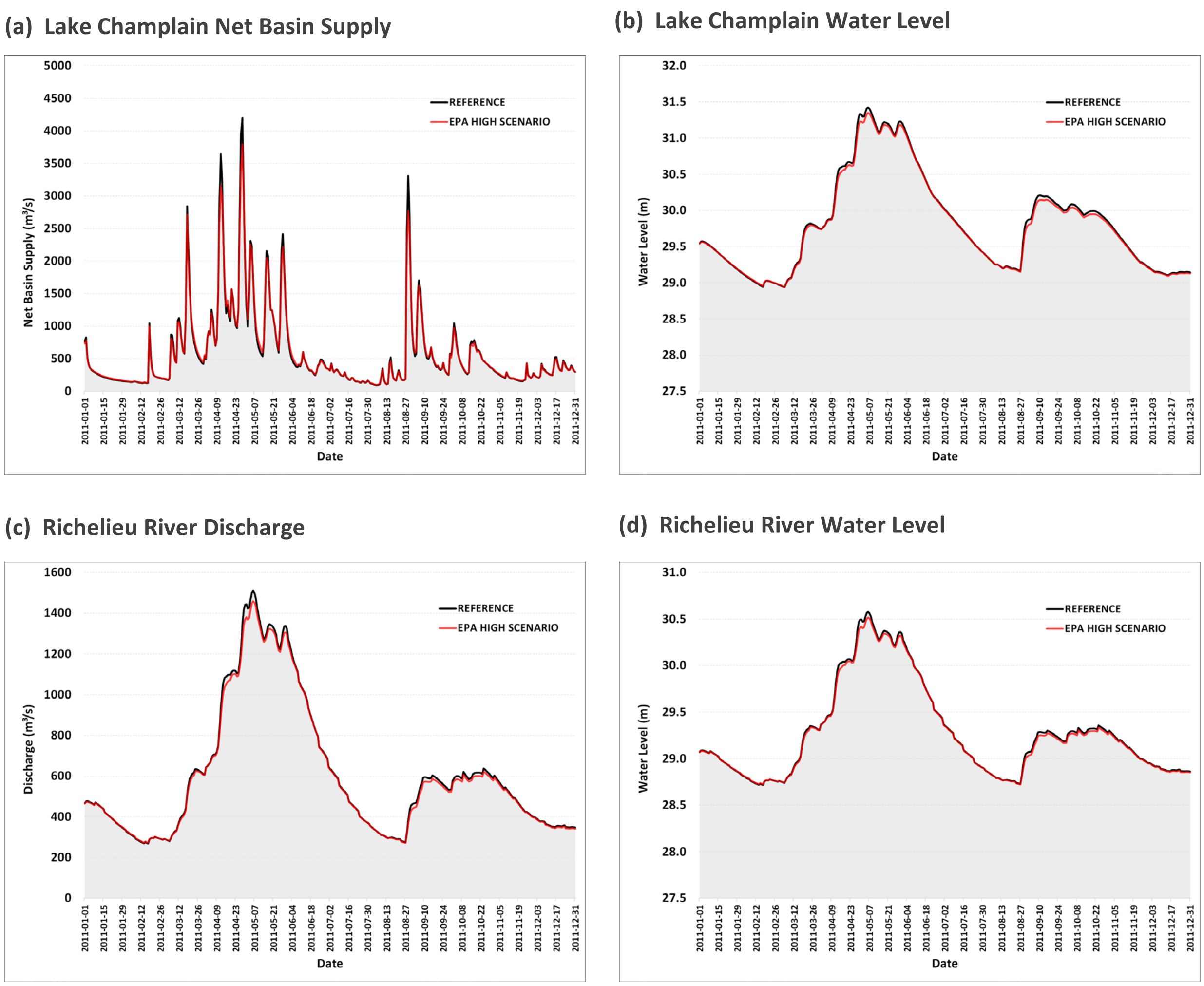
#	WATERSHED (WT GAIN %)	MIN		MAX		FLOODED YEAR					AVERAGE	MEDIAN
		YEAR	ATTENUATION	YEAR	ATTENUATION	1973	1983	1984	2011	2013		
1	Great Chazy (1.3%)	1999	0.4%	1996	9.4%	2.5%	0.7%	3.3%	6.0%	5.3%	2.3%	2.1%
2	Little Chazy (1.6%)	1978	-1.4%	2013	14.8%	5.9%	4.8%	4.8%	7.4%	14.8%	4.9%	4.7%
3	Dead Creek (1.5%)	1967	-2.1%	1965	13.5%	0.0%	1.5%	0.1%	0.1%	1.5%	1.4%	1.3%
4	Saranac (0.6%)	1958	-0.4%	2003	5.7%	2.1%	2.9%	2.4%	0.9%	4.5%	2.1%	1.9%
5	Salmon (1.2%)	2009	-1.2%	1961	5.0%	1.5%	0.2%	0.7%	4.0%	2.2%	1.4%	1.0%
6	Little Ausable (0.5%)	2003	-0.1%	1965	5.3%	1.0%	0.6%	1.1%	2.2%	2.1%	1.5%	1.2%
7	Ausable (0.3%)	1994	0.0%	1968	2.2%	0.9%	0.3%	1.4%	0.5%	0.8%	0.9%	0.9%
8	Bouquet (0.5%)	1997	0.0%	1982	5.9%	1.1%	0.7%	2.6%	2.0%	1.6%	1.3%	1.2%
9	Putnam Creek (0.9%)	2005	-1.5%	1991	9.7%	7.1%	1.5%	3.8%	6.6%	0.7%	2.3%	1.6%
10	La Chute (0.6%)	1995	-0.1%	2010	5.4%	0.6%	1.0%	0.8%	3.4%	0.1%	1.7%	1.5%
11	Poultney (1.2%)	1966	1.2%	2011	8.6%	6.5%	2.6%	6.7%	8.6%	3.7%	3.9%	3.7%
12	Otter Creek (5.0%)	1991	-0.8%	1963	25.5%	9.2%	6.8%	7.1%	16.9%	8.9%	9.8%	8.6%
13	Little Otter Creek (9.0%)	1983	8.6%	1965	23.6%	15.1%	8.6%	13.7%	18.4%	12.1%	15.7%	15.6%
14	Lewis Creek (8.2%)	1989	11.9%	1954	28.7%	21.9%	14.8%	17.0%	18.7%	23.9%	21.0%	21.6%
15	LaPlatte (8.9%)	1972	18.8%	1979	40.3%	25.9%	20.8%	21.6%	26.6%	28.4%	26.6%	25.8%
16	Winooski (7.6%)	1991	2.8%	2011	25.4%	17.3%	10.4%	20.4%	25.4%	13.6%	16.4%	16.8%
17	Lamoille (8.7%)	1978	7.6%	2010	25.8%	24.9%	13.8%	18.2%	20.4%	21.1%	17.1%	17.0%
18	Missisquoi (6.6%)	1985	1.3%	2006	20.8%	9.1%	7.9%	7.6%	19.0%	9.2%	9.6%	9.0%
19	De La Roche (8.6%)	1994	1.3%	1977	37.0%	19.0%	17.6%	19.7%	10.3%	15.2%	18.2%	17.9%
20	Aux Brochets (2.1%)	1953	-0.7%	1982	7.8%	1.1%	1.4%	0.4%	1.6%	1.1%	1.1%	1.0%
	LC NBS (4.1%)	**1955**	**4.4%**	**2006**	**14.3%**	**8.0%**	**6.1%**	**10.1%**	**9.7%**	**10.5%**	**8.1%**	**7.8%**
	RR (Fryers) (3.9%)	***1966***	***1.3%***	***2006***	***4.7%***	***2.3%***	***2.1%***	***3.3%***	***3.3%***	***3.1%***	***2.6%***	***2.5%***
	LC Water Level (cm)	***1985***	***2***	***1998***	***11***	***5***	***4***	***6***	***8***	***6***	***5***	***4***
	RR Water Level (cm)	***1966***	***1***	***1998***	***8***	***3***	***3***	***4***	***6***	***4***	***3***	***3***

9.2.2 Effect of EPA wetlands scenario reported on the 2011 flood

The 2011 hydrographs were evaluated at various spatial scales, comparing simulation results related to the current effect of wetlands and the USEPA scenario. Here the results are presented at a daily time step in terms of the NBS simulated by HYDROTEL and flows and water levels supplied by the daily WBM using the aforementioned NBSs as input. Figure 9.7 shows the impact of the USEPA high potential wetland scenario in the LCRR basin on NBS flows (a), LC water level (b), discharge in the RR at the Fryers Rapids (c) and RR water level (Saint-Jean Marina) (d) for 2011 conditions using HYDROTEL and WBM at a daily time step.

Table 9.6 summarizes the USEPA scenario considering the 2011 conditions.

Based on the USEPA scenario, an increase in water storage by adding wetlands could decrease Lake Champlain NBS peak flows by 9.7%; this would lead to a reduction in the lake water level of 8 cm. The benefits would not be the same for the Richelieu River discharges (-3.3%), but the water level reduction would be consistent (- 6 cm) and certainly not negligible. Thus, this scenario is relevant for Lake Champlain and has the potential to provide beneficial effects at the local scale of various river segments located in the state of Vermont.



**Observations are displayed in black and simulations in red.*

Figure 9-7. Impact of the USEPA high potential wetland scenario in the LCRR basin given the 2011 conditions using HYDROTEL and WBM at a daily time step.

Table 9-6. Summary of EPA wetlands scenario impact on NBS flows, LC water level, discharge in the RR at the Fryers Rapids and RR water level (Saint-Jean Marina) for the 2011 conditions.

Wetlands	Lake Champlain Basin	Richelieu River (Fryer)
Area (km²)	21,254	22,055
Wetlands Area (km²)	2,416 (1,551)	2,481 (1,616)
Wetlands Drainage Area (km²)	8,655 (7,749)	8,810 (7,902)
HYDROTEL + WBM (daily time step)		
Decrease of the highest peak (%)	-9.7% (NBS)	-3.3% (DISC.)
Decrease of the highest water level	-8 cm (-0.24%)	-6 cm (-0.20%)

() indicates existing wetland area or relative water level decrease

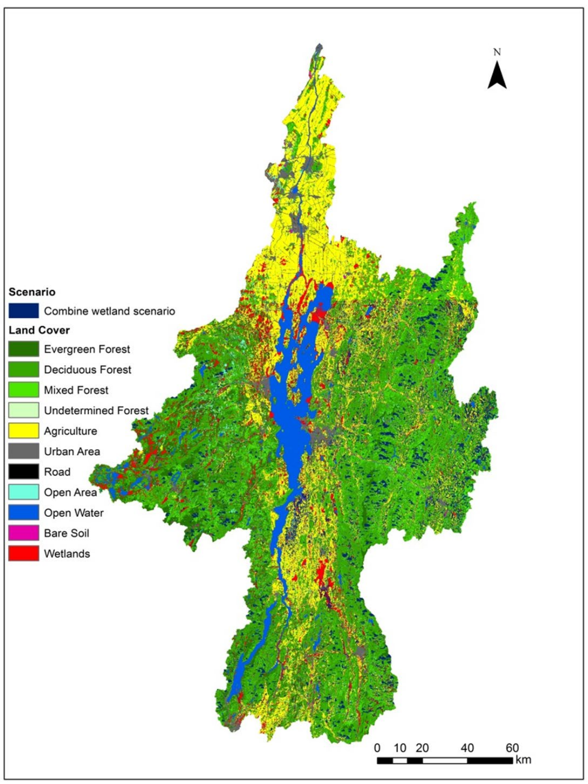


Figure 9-8. General representation of the combined wetland scenarios.

9.3 COMBINING THE WETLAND SCENARIOS

As a final scenario, the DEM-based wetland scenario and the USEPA scenario were combined, resulting in the potential addition of 1,493 km² of wetlands in the Lake Champlain basin (see Figure 9.8)

Table 9.7 presents, for each subwatershed, the resulting distribution of wetland area and wetland drainage area. The same approach was used to assess the outcome of the combined scenarios.

The calculation procedure remains:

- For high flows:

$$\frac{Current\ Wetlands - Wetland\ \ Scenario}{Current\ Wetlands}$$

  where a positive result corresponds to an attenuation.

- For low flows:

$$\frac{Wetland\ \ Scenario - Current\ Wetlands}{Current\ Wetlands}$$

  where a positive result corresponds to an amplification.

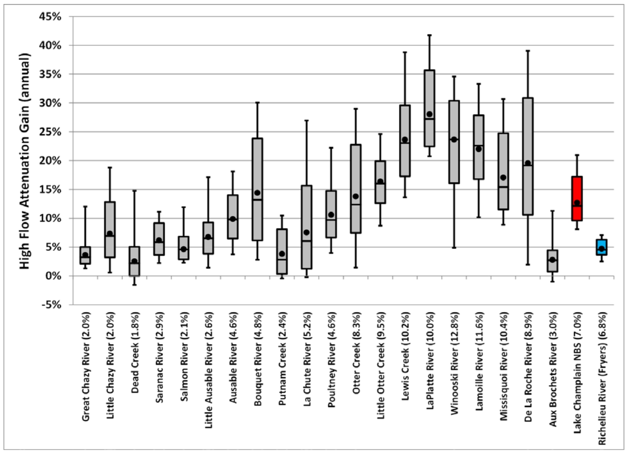
9.3.1 Effect on high flows

Figure 9.9 highlights the impact (annual, spring, summer/autumn) of the combined scenarios on high flow attenuation. Similarly, low flow amplification gains are reported in Appendix III (Figure A3.5). Table 9.8 summarizes the annual effect on (i) high flow attenuation for the 20 major LC subwatersheds, (ii) LC NBS, (iii) RR flows at Fryers Rapids and (iv) water levels of the LC and RR (Marina Saint-Jean); results for specific flood years are also introduced.

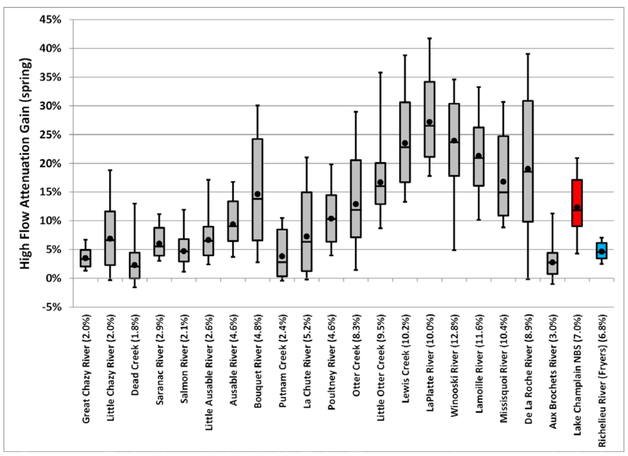
Table 9-7. Spatial impact of the combined wetland scenarios on the LCRR basin for the 20 LC subwatersheds, LC NBS and RR flows at Fryers Rapids.

#	WATERSHED	DRAINAGE (km²)	Wetlands (km²)	Wetlands GAIN (km²)*	vs. Watershed (%)	vs. Watershed GAIN (%)*	W Drainage (km²)	W Drainage GAIN (km²)	vs. Watershed (%)	vs. Watershed GAIN (%)
1	Great Chazy	778	123	15	15.7%	2.0%	384	14	49.4%	1.8%
2	Little Chazy	143	23	3	16.2%	2.0%	77	4	53.9%	3.1%
3	Dead Creek	114	29	2	25.8%	1.8%	65	2	56.8%	1.5%
4	Saranac	1579	230	46	14.6%	2.9%	791	30	50.1%	1.9%
5	Salmon	177	18	4	10.4%	2.1%	95	5	53.7%	2.7%
6	Little Ausable	188	17	5	9.3%	2.6%	105	10	55.7%	5.5%
7	Ausable	1329	137	61	10.3%	4.6%	562	62	42.3%	4.7%
8	Bouquet	621	68	30	10.9%	4.8%	290	35	46.7%	5.6%
9	Putnam Creek	158	16	4	9.8%	2.4%	86	4	54.2%	2.8%
10	La Chute	678	61	35	8.9%	5.2%	210	35	31.0%	5.2%
11	Poultney	1778	203	82	11.4%	4.6%	865	91	48.7%	5.1%
12	Otter Creek	2446	428	204	17.5%	8.3%	1181	219	48.3%	8.9%
13	Little Otter Creek	153	33	15	21.3%	9.5%	88	9	57.7%	5.8%
14	Lewis Creek	203	37	21	18.0%	10.2%	100	19	49.2%	9.6%
15	LaPlatte	118	20	12	16.6%	10.0%	62	19	52.6%	16.1%
16	Winooski	2756	431	352	15.6%	12.8%	1169	511	42.4%	18.5%
17	Lamoille	1866	310	216	16.6%	11.6%	916	209	49.1%	11.2%
18	Missisquoi	2212	385	231	17.4%	10.4%	1015	129	45.9%	5.8%
19	De La Roche	144	28	13	19.5%	8.9%	74	12	51.1%	8.1%
20	Aux Brochets	664	76	20	11.5%	3.0%	239	21	35.9%	3.2%
	LC	**21254**	3039	1488	14.3%	7.0%	9296	1548	43.7%	7.3%
	RR (Fryers)	**22055**	3106	1489	14.1%	6.8%	9469	1567	42.9%	7.1%

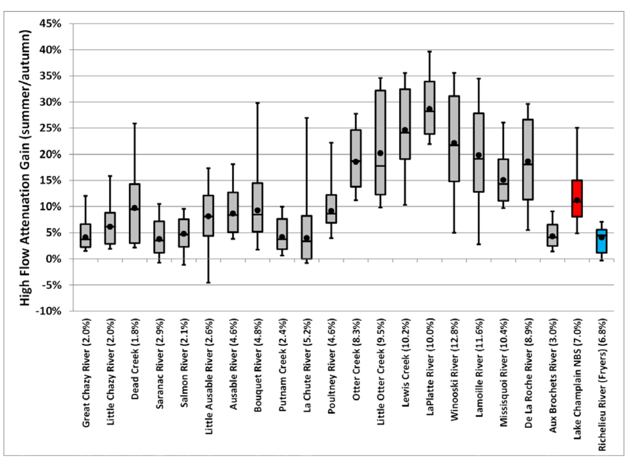
** The gains mean an increase in wetland area (for example, for Great Chazy with the addition of wetlands, 15.7% (13.8% of wetland land cover + 2.0% of additional wetlands) of the watershed is in wetland area.*



(a) (Min; Max; 10th percentile; 90th percentile; Median; Average)



(b) (Min; Max; 10th percentile; 90th percentile; Median; Average)



(c) (Min; Max; 10th percentile; 90th percentile; Median; Average)

Figure 9-9. Gains in high flows attenuation of the combined wetland scenarios on the LCRR basin for the 20 LC subwatersheds, LC NBS and RR flows at Fryers Rapids compare to current conditions, for various temporal scales: (a) annual, (b) spring and (c) summer/fall.

For subwatersheds with a high percentage gain of additional wetland area, a significantly higher impact on high flows is observed, when compared to subwatersheds with smaller percentage gain; that is particularly true for Vermont's subwatersheds. Figure 9.9 illustrates how the impacts vary from year to year in each subwatershed. The annual and spring attenuation gains are similar, since the highest flow occurs most of the time during spring. Figure 9.9 shows that for four (4) subwatersheds (Dead Creek, Putnam Creek, La Chute and Aux Brochets), the annual or spring results include negative impacts (increase of high flows); meanwhile, for four (4) subwatersheds (Saranac, Salmon, Little Ausable, and La Chute), autumn results also include negative impacts. Negative impact can occur when initial water conditions in wetlands and temporality of flooding can increase high flow, but the relative high flow increases are small and limited. Such negative values suggest that for certain years, additional wetlands land could worsen the high flows; but it is important to note that all median or average attenuation gains are positive.

Table 9.8 shows variable maximum or minimum year impacts for all the modelling period and clear contribution of additional high potential wetlands for specific noticeable flood years (1973, 1983, 1984, 2011, and 2013). Based on the 1950-2013 meteorological conditions, combining the wetland scenarios provides a means of highlighting additional reductions in peak flows. Indeed, when compared to the current wetland distribution, increasing the wetland area from 7.3% to 14.3% of the LC basin area could induce a decrease in the highest NBS peak flows at the daily time step by 12.7% on average; and the peak flow at the Fryers Rapids on the Richelieu River (RR) by 4.7% on average. Such reductions are seen as well on water levels of Lake Champlain and Richelieu River (on average, 8 cm on the LC and 6 cm at the St-Jean-sur-le-Richelieu marina). From a pure hydrological modelling point of view, additional wetlands based on the combined large-scale scenario could substantially contribute to flood attenuation and be an effective passive water storage practice.

Table 9-8. Gains in annual high flow attenuation of the combined wetland scenarios on the LCRR basin for the 20 LC subwatersheds, LC NBS, RR flows at Fryers Rapids and LC and RR (Saint-Jean Marina) compared to current conditions.

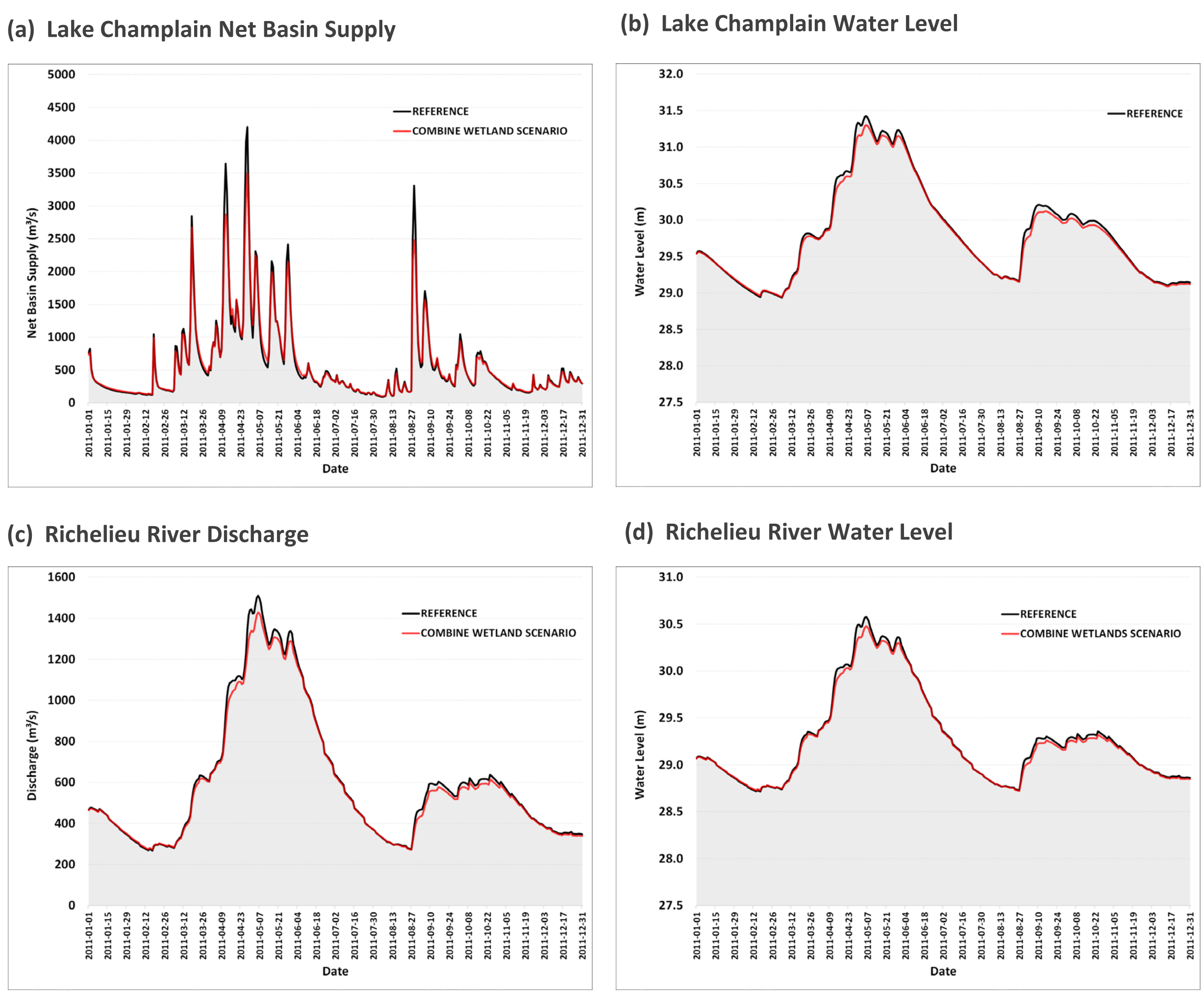
#	WATERSHED (WT GAIN %)	MIN		MAX		FLOODED YEAR					AVERAGE	MEDIAN
		YEAR	ATTENUATION	YEAR	ATTENUATION	1973	1983	1984	2011	2013		
1	Great Chazy (2.0%)	1961	1.3%	1996	12.0%	3.8%	1.8%	4.9%	4.7%	6.7%	3.6%	3.3%
2	Little Chazy (2.0%)	1967	0.6%	2001	18.8%	8.1%	6.4%	6.7%	13.4%	15.3%	7.3%	6.9%
3	Dead Creek (1.8%)	1969	-1.5%	1965	14.8%	0.4%	2.5%	1.0%	2.4%	2.2%	2.6%	2.2%
4	Saranac (2.9%)	1965	2.2%	2006	11.2%	5.5%	4.8%	5.3%	3.5%	8.6%	6.2%	5.8%
5	Salmon (2.1%)	2007	2.3%	1998	11.9%	4.7%	2.7%	4.7%	5.9%	7.0%	4.7%	4.6%
6	Little Ausable (2.6%)	2003	1.4%	1998	17.1%	4.6%	3.7%	6.5%	7.6%	5.0%	6.7%	6.5%
7	Ausable (4.6%)	1965	3.7%	1996	18.1%	10.8%	5.8%	11.7%	13.0%	7.2%	9.9%	9.8%
8	Bouquet (4.8%)	1959	2.8%	2001	30.0%	15.4%	14.8%	17.9%	15.7%	6.6%	14.4%	13.2%
9	Putnam Creek (2.4%)	1975	-0.4%	1969	10.5%	8.6%	2.5%	6.5%	6.7%	2.5%	3.8%	2.8%
10	La Chute (5.2%)	1964	-0.2%	1957	27.0%	3.5%	2.6%	1.7%	19.7%	0.1%	7.5%	6.1%
11	Poultney (4.6%)	1966	4.0%	2011	22.2%	11.7%	8.2%	15.6%	22.2%	8.3%	10.6%	9.7%
12	Otter Creek (8.3%)	1991	1.4%	1963	29.0%	13.0%	9.0%	11.9%	21.2%	10.6%	13.8%	12.4%
13	Little Otter Creek (9.5%)	1983	8.7%	1965	24.6%	15.7%	8.7%	14.3%	19.6%	12.8%	16.4%	16.0%
14	Lewis Creek (10.2%)	1967	13.6%	1998	38.8%	22.7%	15.9%	19.1%	35.6%	26.1%	23.6%	23.0%
15	LaPlatte (10.0%)	1972	20.7%	1979	41.7%	27.5%	22.0%	22.5%	35.9%	30.1%	28.1%	27.2%
16	Winooski (12.8%)	1991	4.9%	2001	34.6%	25.0%	13.0%	26.2%	30.3%	18.3%	23.7%	23.7%
17	Lamoille (11.6%)	1978	10.2%	2011	33.3%	28.6%	16.7%	21.2%	33.3%	25.9%	22.0%	22.6%
18	Missisquoi (10.4%)	1951	8.9%	1992	30.7%	13.6%	12.6%	14.2%	25.6%	17.0%	17.1%	15.4%
19	De La Roche (8.9%)	1994	1.9%	2011	39.0%	21.9%	18.5%	20.7%	39.0%	15.9%	19.5%	19.2%
20	Aux Brochets (3.0%)	1959	-1.0%	1982	11.3%	2.3%	3.0%	1.9%	1.7%	3.8%	2.8%	2.7%
	LC NBS (7.0%)	**1954**	**8.1%**	**2006**	**20.9%**	**12.2%**	**9.1%**	**14.7%**	**16.7%**	**15.5%**	**12.7%**	**12.2%**
	RR (Fryers) (6.8%)	***1966***	***2.5%***	***2006***	***7.1%***	***4.3%***	***3.7%***	***5.0%***	***5.4%***	***4.5%***	***4.7%***	***4.5%***
	LC Water Level (cm)	***2004***	***3***	***1998***	***19***	***10***	***7***	***9***	***12***	***8***	***8***	***8***
	RR Water Level (cm)	***1966***	***2***	***1998***	***11***	***6***	***5***	***6***	***10***	***6***	***6***	***6***

9.3.2 Effect of the combined wetland scenarios on the 2011 flood

The 2011 hydrographs were evaluated to compare the effects of the current wetland distribution with those of the combined wetland scenarios using the aforementioned methodological approach; that is, the use of daily NBSs simulated by HYDROTEL as input to the daily LC WBM. Figure 9.10 shows the effects of the combined wetland scenarios on the LCRR basin NBS flows (a), LC water levels (b), discharges in the RR at Fryers Rapids (c) and RR water levels at Saint-Jean Marina (d) for the 2011 conditions.

Table 9.9 summarizes the effects of the combined scenarios.

Combining the wetland scenarios introduced in this Chapter would have decreased Lake Champlain NBS peak flows by 16.7% and reduced lake water levels by 12 cm. The benefits on the Richelieu River discharges would not have been as large (5.4%), but the reduction in water levels would have been similar (10 cm). Thus, on a daily time scale, large-scale storing of water in wetlands could have provided significant relief in 2011. It remains important to note that such a scenario includes considerable additional storage area and would be challenging to implement.



**Observations are displayed in black and simulations in red.*

Figure 9-10. Effects of the combined wetland scenarios on the LCRR basin given the 2011 conditions using HYDROTEL and WBM at a daily time step.

Table 9-9. Summary of the effects of the combined wetland scenarios on NBS flows, LC water levels, discharges in the RR at the Fryers Rapids and RR water levels (Saint-Jean Marina) for the 2011 conditions.

Wetlands	Lake Champlain Basin	Richelieu River (Fryer)
Area (km^2)	21,254	22,055
Wetlands Area (km^2)	3,039 (1,551)	3,106 (1,616)
Wetlands Drainage Area (km^2)	9,296 (7,749)	9,469 (7,902)
HYDROTEL + WBM (daily time step)		
Decrease of the highest peak (%)	-16.7% (NBS)	-5.4% (DISC.)
Decrease of the highest water level	-12 cm (-0.39%)	-10 cm (-0.33%)

() indicates existing wetland area or relative water level decrease

10 WATER STORAGE MAPPING TOOL

Manual building of an elaborate and specific scenario that is meant to represent water storage on agricultural or other landscapes can be a massive task and require a tremendous amount of time that was beyond the scope of this study. An innovative and alternative approach was developed as part of this project to assess and map water storage capacities on appropriate landscapes, using relevant spatial information and having different potential objectives. A specific GIS tool was developed for this project that has been integrated into PHYSITEL to produce water storage maps.

10.1 WATER STORAGE TOOL

As a general description, the water storage tool refers to an algorithm that allows, if needed, incremental variation of water storage on specific land uses to achieve specified objectives or targets under diverse conditions or limitations using a graphical user interface (GUI) (see Figure 10.1). (Note that for now, the GUI is in French.) The following sections of this report describe aspects of the tool.

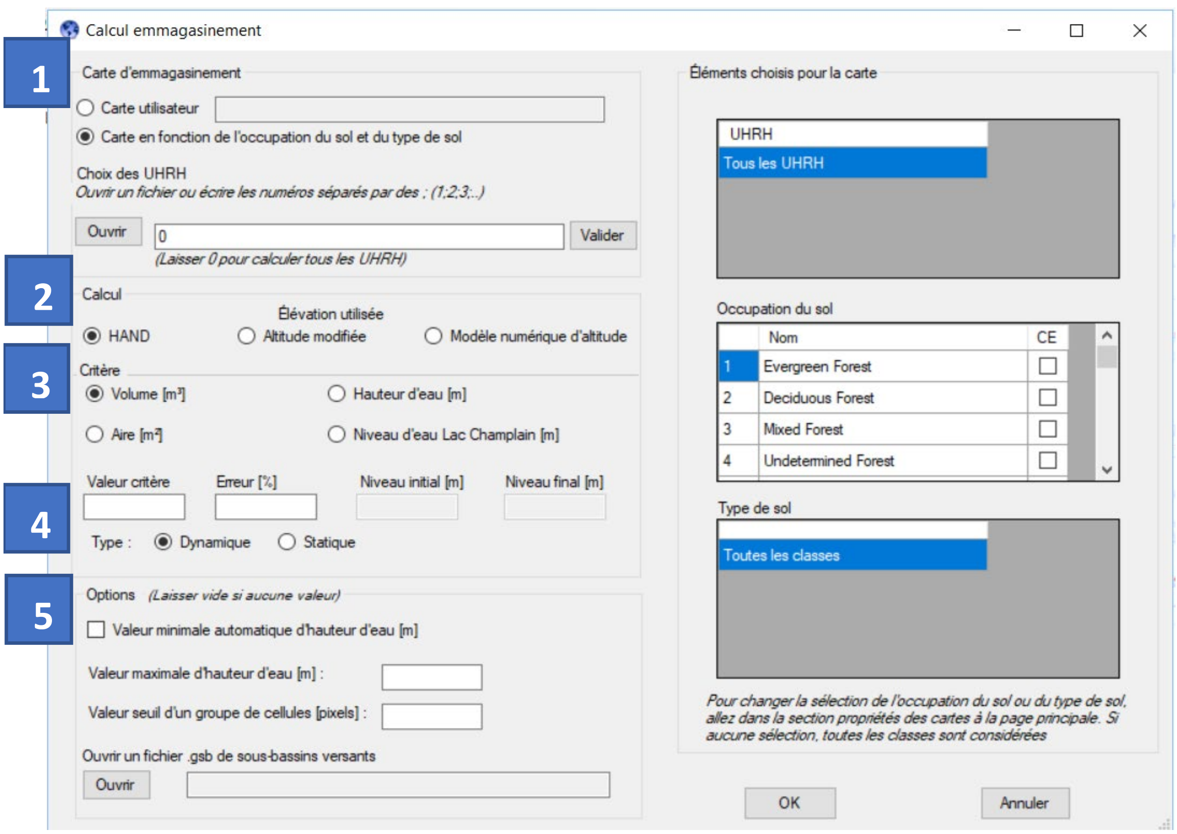


Figure 10-1. Print screen of the graphical user interface of the water storage tool (French only).

10.1.1 Mapping potential water storage

The potential water storage map (labelled as Tag 1, Figure 10.1) is used to delineate locations where it is desired to allow storage. There are two options, either using a user-supplied map or building a potential map based on selected land cover and soil type classes. The user-supplied map is converted into a map with predefined storage areas. Only the selected cells of the map can store water and, therefore, only these cells are considered for storage calculation.

For the other option, default land cover and soil type maps are used to select the land cover and the soil type where it is desirable to store water. For this specific option, the user must open the properties section of the land cover and soil type PHYSITEL project maps, then check the covers to be considered in the calculation. Finally, the last step to create the initial storage map is the optional selection of RHHUs where the water can be stored. The union of all inputs identifies the cells where water can be stored and represents the potential storage map, as shown in Figure 10.2.

10.1.2 Spatial reference for calculation

The next section of the interface (Calcul) (Tag 2, Figure 10.1) deals with the selection of the reference datum map. This reference represents the elevation map to be used for water accumulation; this is the basis of the storage calculation, since the vertical elevation value of each cell must be known to obtain the topography. The lower the vertical elevation of a cell, the more likely it is to store water. There are three different elevation maps that can be used to store water: the HAND map, the modified elevation map and the digital elevation model (DEM) map.

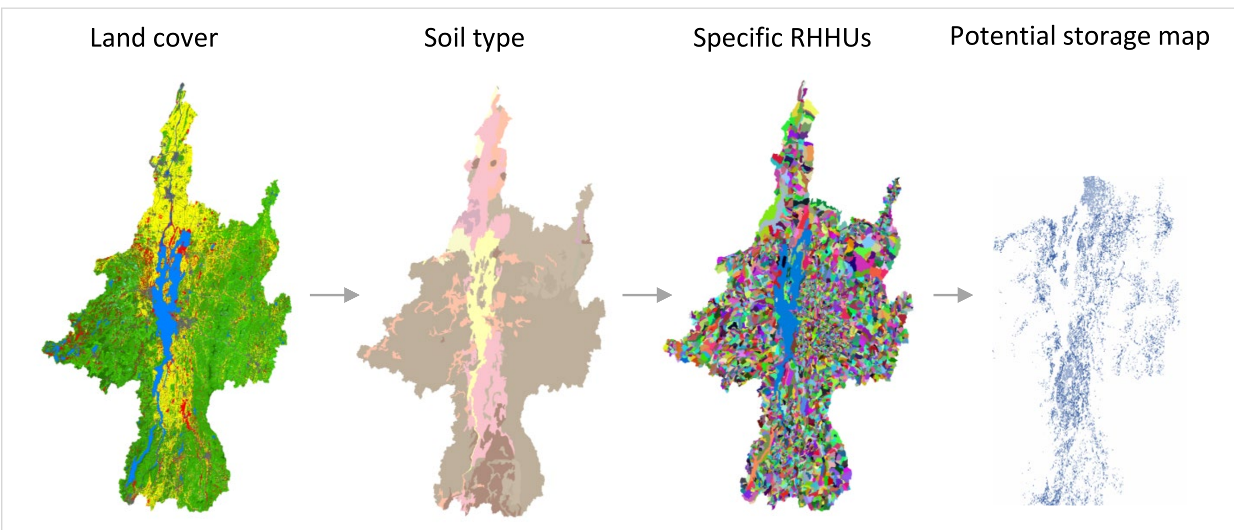


Figure 10-2. Basic steps to build a potential water storage map (PHYSITEL screen capture).

The “Height Above the Nearest Drainage” map (see Figure 10.3), known by the acronym “HAND”, is a conceptual model allowing the normalization of the topography of the ground according to local relative heights at the periphery of the hydrographic network (Nobre, Cuartas, Hodnett, et al., 2011; Nobre, Cuartas, Momo, et al., 2016). The value obtained then corresponds to the water level threshold to cause flooding (Zheng et al., 2018). The HAND value can be seen as a relative assessment of where water would accumulate naturally, corresponding to small HAND values. This method is useful when calculating a dynamic storage map since it integrates the notion of water flow from one cell to another. In the case of the Shuttle Radar Topography Mission (SRTM)-30m DEM the relative vertical height accuracy is less than 10 m. Note that using the HAND conceptual model would not be impacted by the DEM vertical accuracy as this model provides relative information.

10.1.3 Water storage target

To build the water storage map, the program must know how much water needs to be stored or the targeted parameter for the water storage calculation (Tag 3, Figure 10.1). The tool has four (4) options to specify the target, either a volume in cubic meters, an area in square meters, a water level in meters or a reduction of water level in Lake Champlain (specific to the LCRR watershed). This section refers to the calculation criteria in the GUI: volume, area, water height and level of Lake Champlain, as displayed in Figure 10.4.

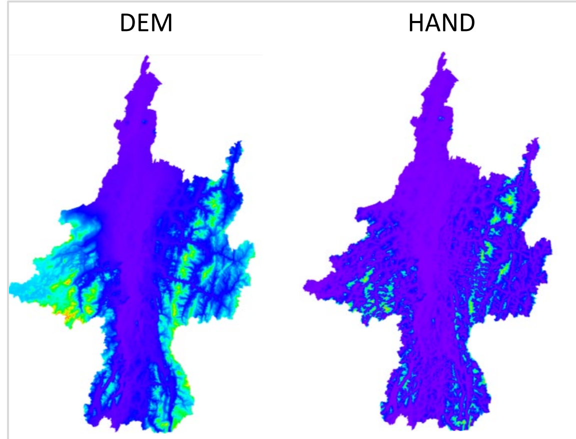


Figure 10-3. Reference elevation map (PHYSITEL print screen).

One of the options of the mapping tool is to specify a maximum volume or storage area. Once the targeted value is met, the accumulation algorithm stops and the final storage map is built. For these two targets, the user must specify the value of the volume or the area and indicate the tolerated error in percentage. The water height criterion corresponds to a threshold water height on a cell of the storage map.

Finally, the option of lowering the Lake Champlain water level is specific to this project. It calculates the total volume of water that must be stored to produce a decrease in Lake Champlain water level, as governed by a level-stored volume rating curve (see Figure 10.5 below). This specific option must be constrained to RHHUs located upstream of Lake Champlain.

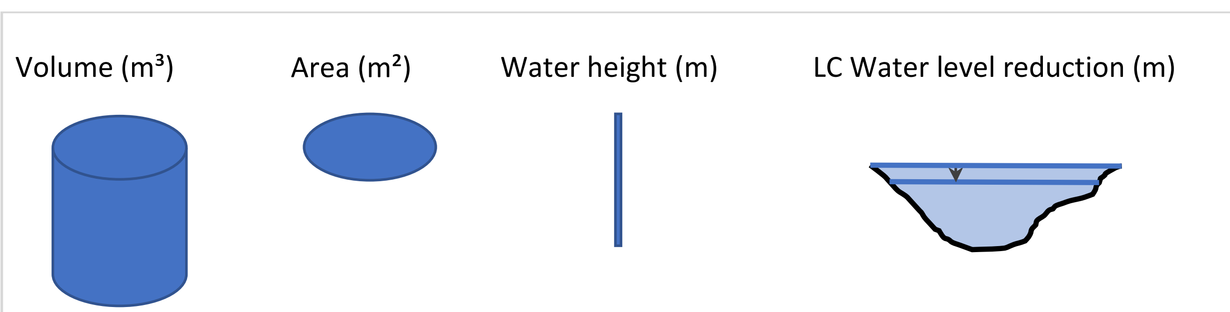


Figure 10-4. Calculation criteria in the water storage mapping tool.

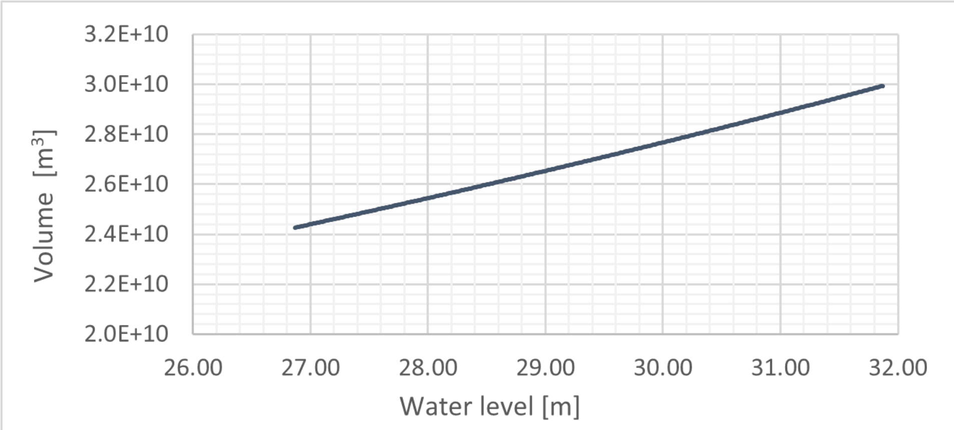


Figure 10-5. Relationship between the water level of Lake Champlain and the volume.

10.1.4 Type of storage: dynamic and static

The type of storage, static or dynamic, must also be specified (Tag 4, Figure 10.1). Static means there is no flow or movement of water over the flooded surface; in other words, water fills in the DEM or the HAND map. On the other end, dynamic aims to include the notion of flow and movement of water into the storage areas. The static approach when using the HAND map as a reference can represent water overflowing from the river network onto adjacent land (i.e., floodplain area). The differences between these types of storage are displayed in Figure 10.6.

One of the advantages of the mapping tool based on HAND values is in the dynamic nature of storing water. The water stored on each cell has different, non-uniform elevations. Water is stored by adding water according to the minimum DEM value of a RHHU, up to a maximum value. Therefore, each RHHU is independent of the others and their respective minimum elevation values are considered when running the algorithm. This makes it possible to divide the territory into different subwatersheds. It is particularly useful when the storage map covers a large area and where there should not be any dependency between two RHHUs that are far apart from each other.

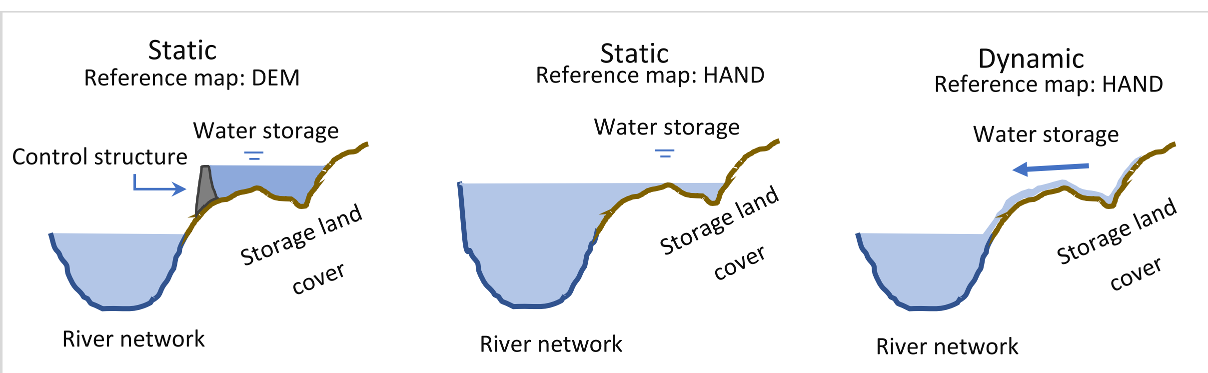


Figure 10-6. Water accumulation in the storage area.

10.1.5 Water storage options

Different options can be added to the input parameters, allowing the user to specify certain characteristics or limitations (Tag 5, Figure 10.1). The automatic minimum water height option is used to find the minimum height to be achieved (i.e. the volume or area target value specified by the user). Another option is to set a maximum value for the water height to be stored on land cover cells. The total volume and area must be reached while satisfying the maximum value. Otherwise, it could happen that the maximum water height would not be sufficient to meet the targeted volume or area.

Finally, a pixel threshold value can be specified to filter results and limit flooding at specific locations. This option allows water to be stored on a cell if the number of available adjacent cells for water storage is greater than the threshold value specified by the user. The intent here is to determine which flooded cells are grouped together and to eliminate isolated cells.

10.2 ANALYSIS OF THE LAKE CHAMPLAIN AND RICHELIEU RIVER (LCRR) BASIN

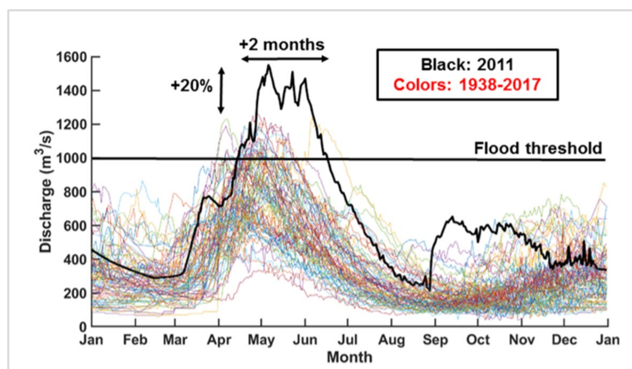
This section analyzes the storage capacity of agricultural land of the LCRR basin. This analysis is based on the 2011 event when there was significant flooding. The goal is to visualize the possible storage in the basin. Figure 10.7 illustrates discharges (in m^3/s) at the Fryers Rapids hydrometric station for the years 1938-2017, with the black curve representing year 2011. The black horizontal line represents the threshold flow above which there is flooding.

Integrating the area under the 2011 curve above the aforementioned threshold value corresponds to approximately 1.612×10^9 m^3 of water. Similarly, we can determine the average flood volumes for all other years. For this period, an inter-annual average volume of 7.205×10^8 m^3 is found above the flood line, which is approximately 45% of the 2011 volume above the line. The difference between these two volumes is equivalent to 8.915×10^8 m^3. Storing this specific volume and then releasing it later during times when the river had capacity between the actual flow and flood flow would transform the 2011 flood into an average year flood. The storage mapping tool was applied for the LCRR basin, to compare the areas needed for storing this volume.

For this exercise, water storage was allowed on agricultural land for all soil types. The tool was developed to limit the water storage based on both the land use and the soil type, giving more flexibility to the tool; however, in this study we have solely controlled the land use option. In addition, to obtain a decrease in the water level of Lake Champlain, only RHHUs flowing into the lake were pre-selected. Finally, to filter the map, a threshold of 1000 pixels was applied on the storage map and an error of 0.5% was set for the calculation.

Four different analyses were performed according to different inputs. These analyses are introduced in Table 10.1. Analysis #1 evaluates storage for the 2011 flood volume, while #2-4 are applied to the average flood volumes for the LCRR.

The storage maps resulting from the four tests are illustrated in Figure 10.8. The last two (#3 and #4) include insets to magnify the details of the cells.

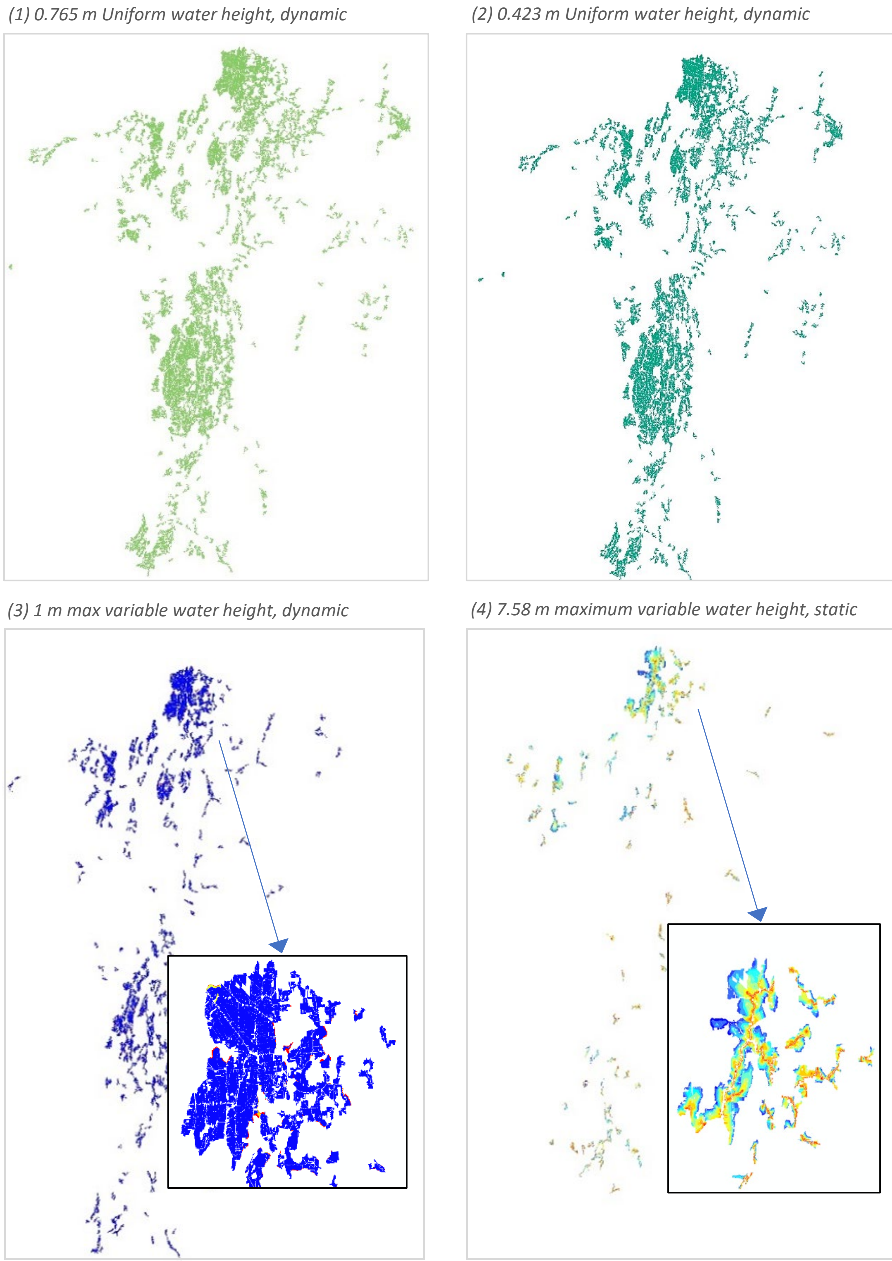


Each year is represented by a different color,while 2011 is in black. (Figure taken without the permission of the publisher from Lucas-Picher et al., 2019)

Figure 10-7. Daily flows of the RR at the Fryers Rapids hydrometric station for the 1938–2017 period.

Table 10-1. LCRR watershed data inputs and results for water storage map creation.

Analysis	1	2	3	4
Volume [$10^8 m^3$]	16.12	8.915	8.915	8.915
Threshold error [%]	0.5	0.5	0.5	0.5
Storage type	Dynamic	Dynamic	Dynamic	Static
Option	Automatic minimum water height	Automatic minimum water height	Maximum water height value	-
Water height [m]	0.765 *Uniform water height*	0.423 *Uniform water height*	1 m maximum *Variable water height*	7.58 m maximum *Variable water height*



Insets are zoom in areas to improve the rendition of the water height variation.

Figure 10-8. Water storage maps for four modelled conditions.

For the first analysis, the minimum water height elevation to store the target volume of 1.612×10^9 m^3 corresponds to 0.765 m. This water depth was applied to all cells making up the initial potential storage map. This value means that a water depth below 0.765 m would not meet the volume to be stored. This storage corresponds to an area of 2,108 km^2, or the equivalent of 46 km x 46 km storage area. Given the considerable height of water on each cell of the map, it is obvious this volume cannot be stored entirely.

For the second analysis, the minimum water elevation value was 0.423 m. This value was distributed evenly over the initial potential storage map. The area of 2,108 km^2 remained unchanged. With the chosen options, reducing the volume to be stored by 45%, the water depth of the cells also decreased by 45%. It would therefore take 0.423 m of water on the entire storage map to reduce the 2011 floods to the average flood value of the other years.

The third analysis required a maximum water depth of 1 m for a dynamic storage. The final volume corresponds to 8.888×10^8 m^3 for a 0.3% error and an area of 902 km^2. Most of the cells store 1 m of water and some cells on the outskirts of agricultural areas have a water depth of less than 1 m. This uniformity is caused by the elevation plane of the terrain. To see these areas properly, an inset is provided in Figure 10.8 that magnifies a portion of the storage map. Colors other than blue represent depths less than 1 m.

Finally, in the fourth (static storage) analysis, water was added to fill in the depressions in the elevation map. This resulted in the greatest changes in water elevation at the shorelines of existing rivers and lakes, which are the areas with the lowest elevations. Water depths decreased as the surrounding landscape was flooded. The red color in Figure 10.8 represents the greatest change in water depth(at existing shorelines). This map allowed for the storage of a final volume of 8.918×10^8 m^3 for a 0.03% error. The flooded area is 239 km^2, equivalent to a square of 15.5 km x 15.5 km. The maximum water depth is 7.58 m, the average is 3.7 m and the standard deviation is 2.1 m.

Water storage on agricultural land of the LCRR basin could reduce future flooding. According to the analyses carried out, the height of water on cells would vary between 0.423 and 7.58 m, which is rather large. When limiting to small water height, the required areas for storing the 2011 volume are very large, but smaller storage areas would require high water height retention capacities. Therefore, other land covers would have to be considered as potential areas for water storage. This would increase the number of admissible cells and decrease the required water levels and area.

From a global perspective, this water storage mapping tool can provide an efficient and effective approach to converge rapidly to a first large-scale approximation to store water or even map potential flooding areas to support local queries or define where flood mitigation efforts should be concentrated.

11 KEY OBSERVATIONS AND CONCLUSIONS

Based on this study, some key elements can be highlighted. The PHYSITEL/HYDROTEL hydrologic modelling platform certainly is useful to assess flow regulation services provided by wetlands. The combined use of HYDROTEL and ECCC daily WBM is an efficient framework to model discharge into the Richelieu River at the Fryers Rapids gauge station and water levels in Lake Champlain and Richelieu River (Saint Jean Marina). The modelling framework is suitable to assess various water storage scenarios. It is noteworthy that the PHYSITEL and HYDROTEL integration of the LCRR basin is readily available to potential users, with basic training and software license. Note, however, that the GUI is currently only in French.

Existing wetlands play a key role in attenuating high flows and flooding and also amplifying low flows in the LCRR subwatersheds. Thus, wetlands affect daily Lake Champlain NBSs and water levels, governing water levels and discharges in the Richelieu River. The simulation results clearly demonstrated that wetlands provided flow and water level attenuation services during the 2011 flood.

Construction of watershed storage scenarios (wetlands and flooding farmland) remains challenging, but an efficient hydrological-GIS modelling framework was used to design and assess them. The study found that increasing water storage within the watershed to reduce flood risk was a worthy and valuable investigation.

The actual study focused on four exploratory independent scenarios:

1. storing water on riparian agricultural landscapes;
2. a first DEM-based wetland addition scenario;
3. USEPA high potential wetland scenario; and
4. a combination of the last two wetland scenarios.

The scenarios (corresponding to additional storage areas of 2,256 km^2 of flooded farmland, 647 km^2 of wetlands, 865 km^2 of wetlands, and 1,488 km^2 of wetlands) highlighted the potential of achieving additional gains to reduce LC NBSs and water levels, and to a lesser extent, the RR peak flows and water levels. These results clearly demonstrate that:

- water storage on riparian agriculture land within the LC watershed could provide, on average, reductions of the annual high flow of the LC tributaries of 1% to 52%; thereby reducing the average annual LC NBS high flow by 15%, the annual RR high flow by 2%, the LC annual high water level by 4 cm and the RR annual high water level by 3 cm.

- construction/restoration of wetlands could provide, on average, reductions of the annual high flow of the LC tributaries by 0.7% to 13%, reducing the average annual LC NBS high flow by 6.3%, the annual RR high flow by 2.6%, the LC annual high water level by 5 cm and the RR annual high water level by 3 cm.

- construction of wetlands according to the USEPA scenario could provide, on average, reductions of the annual high flows of the LC tributaries by 0.9% to 26.6%, reducing on average the annual LC NBS high flow by 8.1%, the annual RR high flow by 2.6%, the LC annual high water level by 5 cm and the RR annual high water level by 3 cm.

- combining wetland scenarios (1) and (2) could provide, on average, reductions of the annual high flows of the LC tributaries by 2.6% to 28.1%, reducing on average the annual LC NBS high flow by 12.7%, the annual RR high flow by 4.7%, the LC annual high water level by 8 cm and the RR annual high water level by 6 cm.

All scenarios demonstrated success in reducing high flows, improving low flows, decreasing peak NBSs and discharges and decreasing water levels. In terms of efficiency, combining both wetland scenarios offers the most interesting gain. However, wetland construction/restoration or flooding farmland (riparian agricultural land) would require extensive surface areas, raising feasibility and acceptability issues.

Table 11.1 introduces the land covers that were considered in the development of the agricultural landscape water storage scenarios. It is obvious that implementing agricultural storage would impact substantial farmland areas and be very challenging to implement. Implementing additional wetlands would also be challenging and would affect both forested areas and farmland. Implementation of any large-scale water storage scenario would also require long-term field work, but would certainly provide hydrological benefits.

Adding wetlands and/or flooding farmland would require extensive surface area requirements. Given existing policies, programs and regulations in Canada (e.g., Quebec Bill 132 - An Act respecting the conservation of wetlands and bodies of water) and/or in the United States (e.g., programs managed by the USDA Natural Resources Conservation Service and the US Fish and Wildlife Service, and Vermont and New York States' Departments of Environmental Conservation), fostering restoration and construction of wetlands instead of flooding farmland might provide a socially-acceptable framework to build resilience over time in the LCRR basin, at least at the local subwatershed levels.

One of the legacies of the project is a new tool available in PHYSITEL to identify potential water storage areas given a pre-estimated runoff volume to be stored. The LCRR HYDROTEL modelling project is available to assess multiple scenarios for each subwatershed, but ultimately for any scenario, there is a need to conduct comprehensive studies, including:

- a flood inundation mapping investigation using as input to a hydraulic model the output of HYDROTEL (i.e., simulated flows) to assess the potential impact of reducing the water levels by specified amounts in the LC and RR, respectively;
- an assessment of the effect on low flows; and
- a cost-benefit analysis including total costs (e.g., construction, easement payments, ...) and total benefits (e.g., avoided damages, valuing environmental goods and services...).

Table 11-1. Land cover involved in farmland water storage and wetland scenarios.

Scenario	Lake Champlain Basin				Richelieu River Basin (Fryers)			
	AGRI	WET DEM	EPA H	COMBINED	AGRI	WET DEM	EPA H	COMBINED
Total additional storage area	2,256	647	865	1,488	2,471	649	865	1,489
Affected land cover classes								
Evergreen Forest	-	84	136	215	-	84	136	215
Deciduous Forest	-	384	158	534	-	385	158	535
Mixed Forest	-	119	173	285	-	119	173	285
Agriculture	2,256	43	294	332	2,471	44	294	334
Others	-	17	104	121	-	17	104	121

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APPENDIX I - List of completed tasks

Tasks completed during the September 2019 to November 2020 period included the following:

1 Analysis of an existing PHYSITEL/HYDROTEL project supported by FMMM[6], including spatial and hydrometeorological data.

2 Required update of spatial data (digital elevation model, land cover, soil type).

3 Development and integration of the LCRR watershed using the latest version of PHYSITEL/HYDROTEL.

4 Calibration and validation of HYDROTEL including a specific calibration for year 2011.

5 Estimation of the stream flow regulation services provided by the current spatial distribution of wetlands within the LCRR watershed.

6 Preliminary, back-of-the-envelope, assessment of the additional surface area of wetlands and flooded agricultural landscapes required to reduce the 2011 peak flow.

7 Combining HYDROTEL Lake Champlain net basin supply with Environment and Climate Change Canada's (ECCC) new daily water balance model (WBM) to simulate Lake water level and Richelieu River discharge.

8 Assessment of a riparian agricultural landscapes water storage scenario using HYDROTEL wetlands modules.

9 Development of a simplified approach to design wetland construction/restoration scenarios.

10 Evaluation of two wetland construction/restoration scenarios.

11 Development of a complete water storage mapping tool.

12 Drafting of the Watershed Storage Progress and Final reports.

[6] Application of a high-resolution distributed hydrological model on a U.S.-Canada transboundary basin: Simulation of the multi-year mean annual hydrograph and 2011 flood of the Richelieu River basin (Lucas-Picher et al. 2020).

APPENDIX II - General description of the wetland modules of HYDROTEL

This section presents the basic concepts behind the wetland modules of HYDROTEL. A complete description can be found in the work of Fossey et al. (2015). It is noteworthy that storage on farmland was simulated using the wetland modules, but the parameterization was adapted to reflect the anticipated behaviour of flooded farmland. A schematic representation of the modules is presented in Figure A2.1.

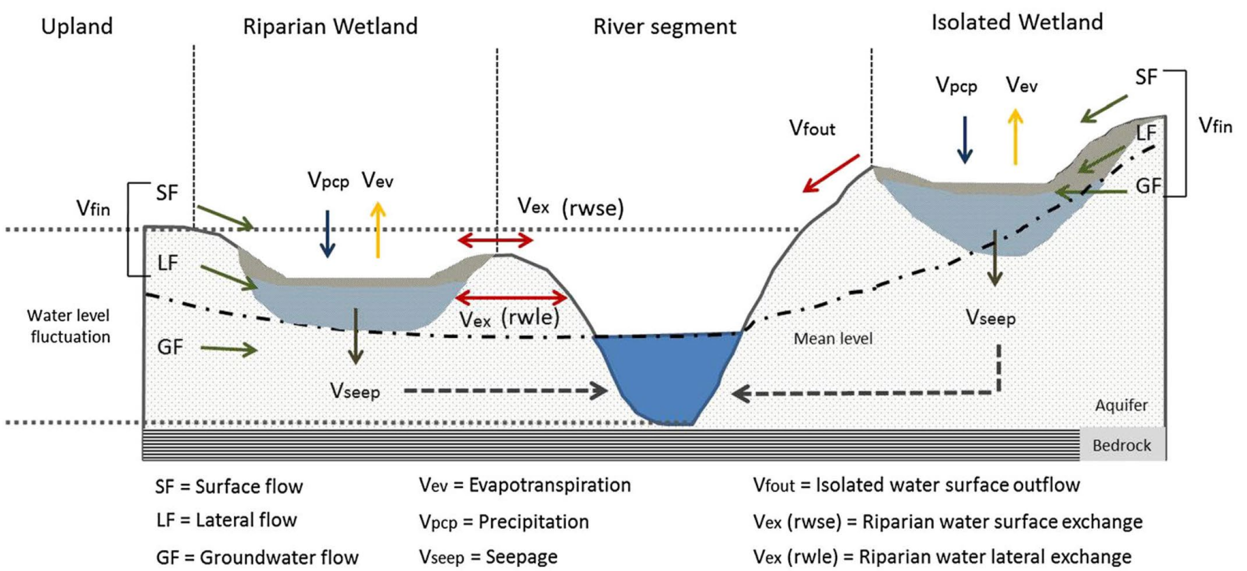


Figure A2.1. Scheme of water exchanges through isolated or riparian wetlands (taken from Fossey et al., 2015 without the permission of the publisher).

As mentioned, HYDROTEL provides specific modules to simulate the hydrological processes of each type of wetlands (isolated, riparian) at the scale of each RHHU. The wetland module simulates water interception from precipitation, snow melt and runoff (surface and subsurface) from the contributing area (i.e. the wetland drainage area), evapotranspiration, infiltration at the bottom of each wetland (contributing to base flow), water storage and outflow. For riparian wetlands, the module also simulates direct water exchanges and interactions with the adjacent river segment through overland runoff and river bank flow. Also at the scale of each RHHU, isolated and riparian wetlands are numerically grouped to form an equivalent isolated wetland or equivalent riparian wetland where the total area and drainage area of the isolated and riparian wetlands are conserved.

It is not the objective here to present all the equations and supporting algorithms of the wetland modules, but it is important to spell out specific notions that contributed to the development of the wetland and water storage scenarios.

At the RHHU scale, the water budgets of equivalent wetlands include specific parameters governing the water volume capacities of wetlands. Additional wetlands will have equivalent parameters to those of existing and dominant wetlands within the subwatersheds (i.e., computational units - RHHUs) or average parameter values for RHHUs without exiting wetlands (see Table A2.1). Such parameters are based on previous work and surveyed literature.

Table A2.1. Average parameter values affecting normal and maximal water volumes and release of water from wetlands.

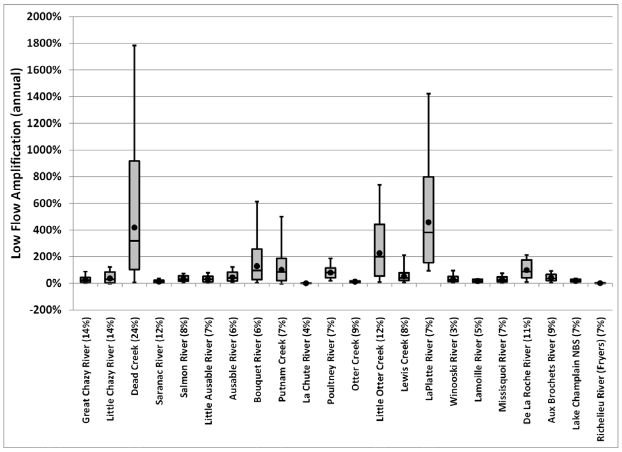
Type	Ratio (Normal Area / Maximal Area)	Normal water height (m)	Maximal water height (m)
Average wetlands	0.30	0.20	0.85

From a general point of view, wetlands intercept water and release some according to specific relationships. The rate of release depends on the normal and maximal volumes of water, which are related to a normal water height with normal wetted area and maximal water height with maximal wetted area, respectively. The maximal wetted area is normally determined from the wetland area of the land cover map.

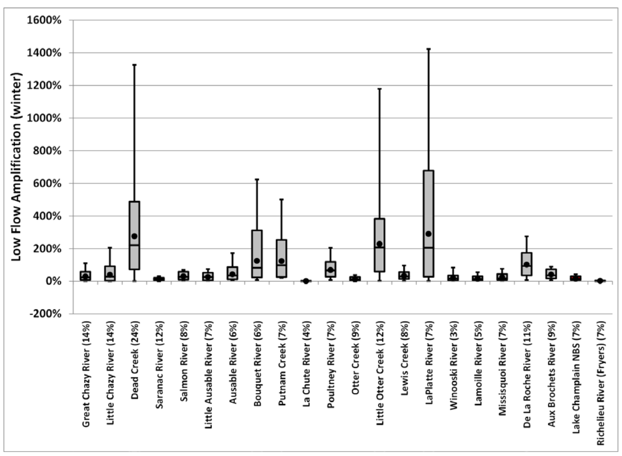
APPENDIX III - Impact of wetland and water storage scenarios on low flows

It is also important to mention that low flow amplification can result in a very large relative variation, given the small magnitude of low flows. The figures below provide evaluation of the impacts of the wetland storage scenarios on low flows.

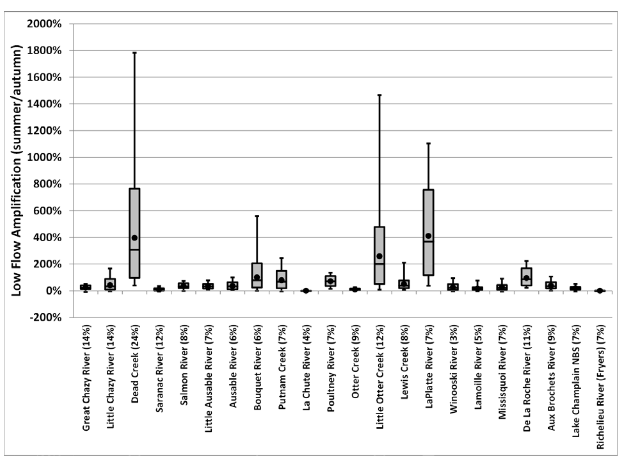
Current wetland distribution in the LCRR basin



(a) (Min; Max; 10th percentile; 90th percentile; Median; Average)



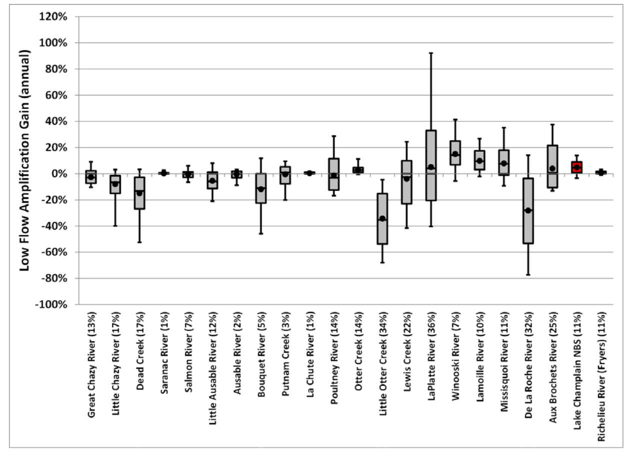
(b) (Min; Max; 10th percentile; 90th percentile; Median; Average)



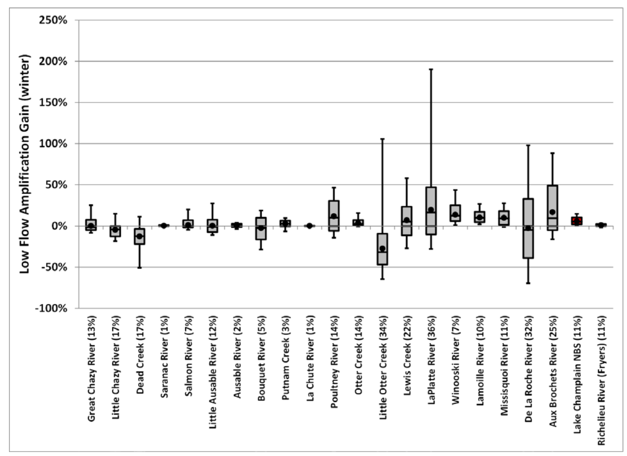
(c) (Min; Max; 10th percentile; 90th percentile; Median; Average)

Figure A3.1. Impacts of current wetlands on low flow amplification of the 20 LC subwatersheds, LC NBS and RR flows at Fryers Rapids for various temporal scales: (a) annual, (b) winter and (c) summer/fall.

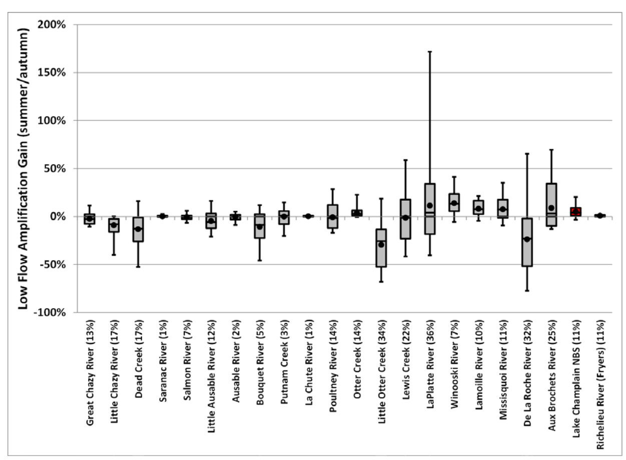
Riparian agricultural landscapes water storage scenario



(a) (Min; Max; 10th percentile; 90th percentile; Median; Average)



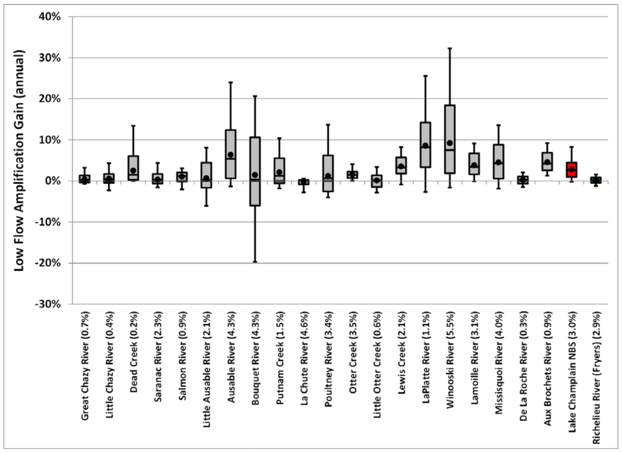
(b) (Min; Max; 10th percentile; 90th percentile; Median; Average)



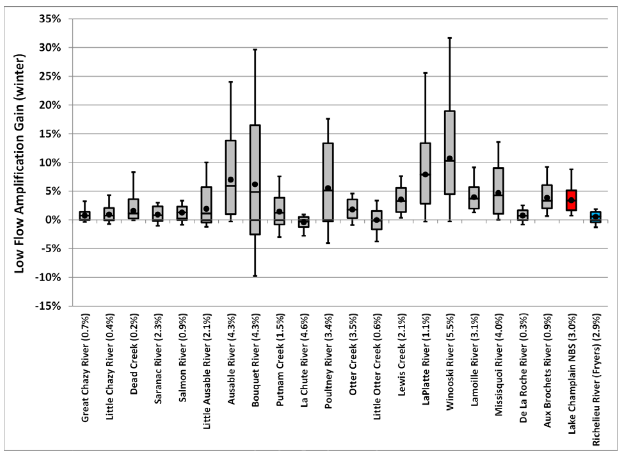
(c) (Min; Max; 10th percentile; 90th percentile; Median; Average)

Figure A3.2. Gains in low flow amplification due to storing water on riparian agricultural landscapes of the LCRR basin for the 20 LC subwatersheds, LC NBS and RR flows at Fryers Rapids with respect to current conditions for various temporal scales: (a) annual, (b) winter and (c) summer/fall.

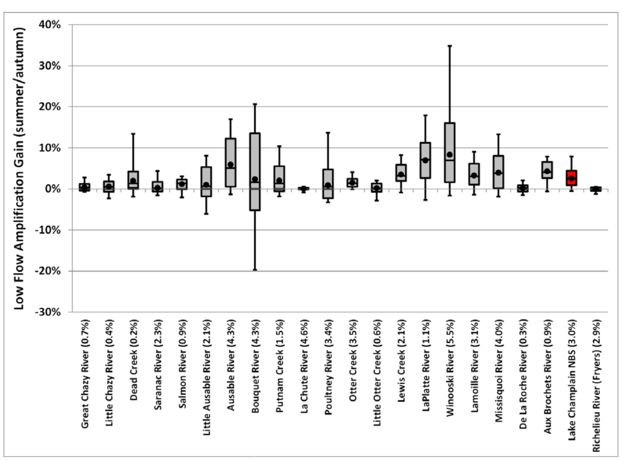
Wetlands construction/restoration scenario based on spatial data



(a) (Min; Max; 10th percentile; 90th percentile; Median; Average)



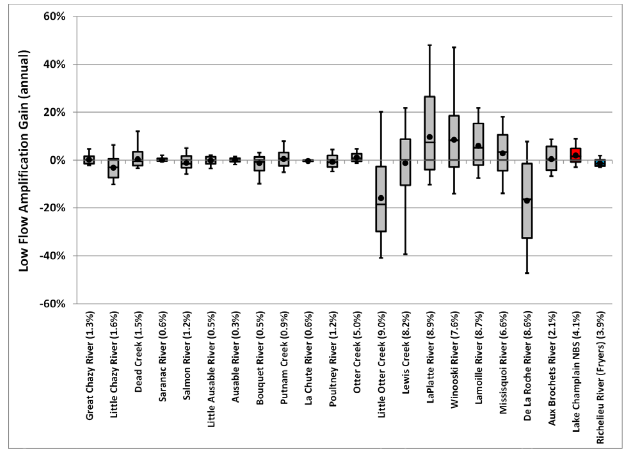
(b) (Min; Max; 10th percentile; 90th percentile; Median; Average)



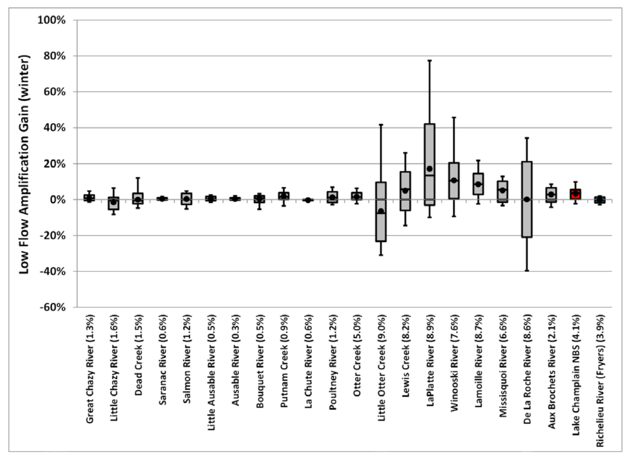
(c) (Min; Max; 10th percentile; 90th percentile; Median; Average)

Figure A3.3. Gains in low flow amplification when adding 652 km^2 of wetland in the LCRR basin for the 20 LC subwatersheds, LC NBS and RR flows at Fryers Rapids compared to current conditions for various temporal scales: (a) annual, (b) winter and (c) summer/fall.

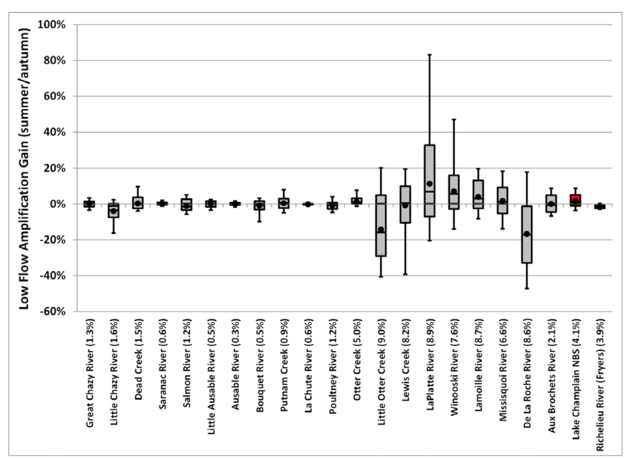
USEPA wetland scenario



(a) (Min; Max; 10th percentile; 90th percentile; Median; Average)



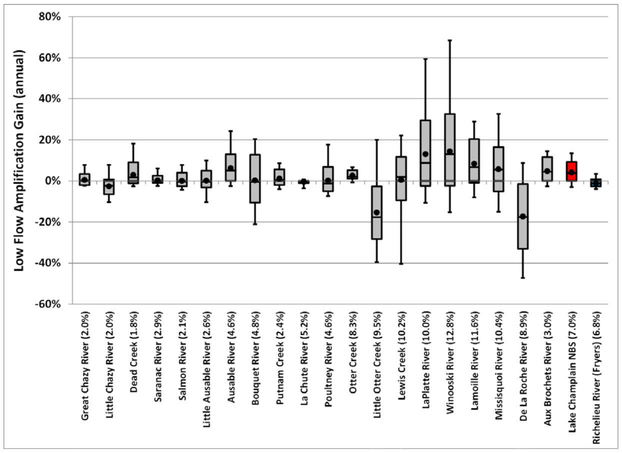
(b) (Min; Max; 10th percentile; 90th percentile; Median; Average)



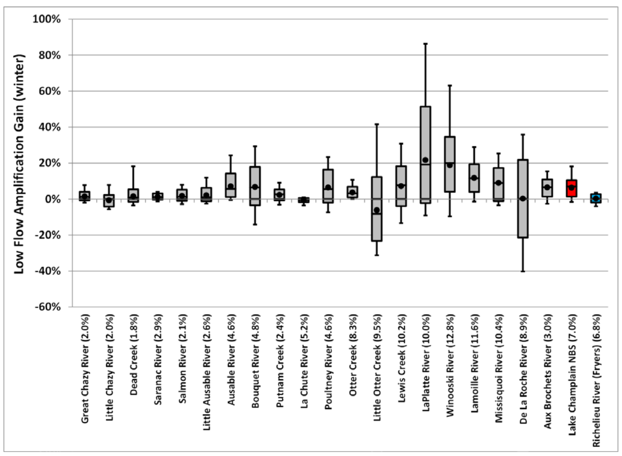
(c) (Min; Max; 10th percentile; 90th percentile; Median; Average)

Figure A3.4. Gains in low flow amplification of the USEPA wetland scenario on the LCRR basin for the 20 LC subwatersheds, LC NBS and RR flows at Fryers Rapids compared to current conditions for various temporal scales: (a) annual, (b) winter and (c) summer/fall.

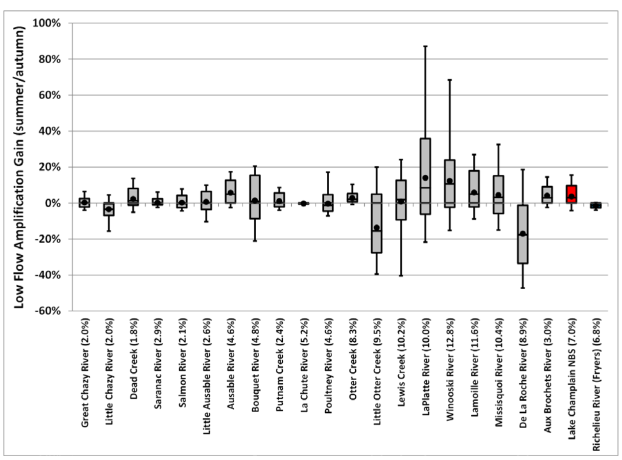
Combined wetland scenario



(a) (Min; Max; 10th percentile; 90th percentile; Median; Average)



(b) (Min; Max; 10th percentile; 90th percentile; Median; Average)



(c) (Min; Max; 10th percentile; 90th percentile; Median; Average)

Figure A3.5. Gains in low flow amplification of the combined wetland scenarios on the LCRR basin for the 20 LC subwatersheds, LC NBS and RR flows at Fryers Rapids compared to current conditions for various temporal scales: (a) annual, (b) winter and (c) summer/fall.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