**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**

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Table of content

Figures

Tables

Background and summary

The scope of this study was built around four basic questions: (i) Why should we study upland storage? (ii) What is the role of wetlands on net basin supply (NBS), flows, and water levels in the Lake Champlain and Richelieu River (LCRR) basin? (iii) What would be the additional benefits of flooding farmland? and (iv) What would be the effect of additional wetlands?

The answers to the first question is twofold. There is a well-documented event that clearly showed that wetlands can alleviate flood, namely the Otter Creek watershed between Middlebury and Rutland, Vermont, during Tropical Storm Irene, August, 28, 2011; and a global effect at the watershed scale as illustrated in several theoretical studies. In the former actual case study, wetlands and floodplains protected Middlebury, from as much as $1.8 million in flood damage during Tropical Storm Irene, as reported by a University of Vermont study (Watson et al., 2016). The study was the first to calculate the economic benefits that wetlands and floodplains could provide during the major storms that struck the US East Coast in recent years. Researchers analyzed 10 flood events to estimate the value of the Otter Creek floodplains near Middlebury. According to the study, the natural barrier saves the town an average of $126,000 to $450,000 per year, or up to 78 percent of potential damages. In the latter theoretical case study, distributed hydrological modelling studies have shown that wetlands generally reduces flows on the rising limb, knock off the peak flow while slightly increasing flows on the recession of a storm hydrograph. The overall effect is a combined shift and damping of the storm hydrograph of varying magnitudes as will be demonstrated in this report.

For this project, we used the PHYSITEL/HYDROTEL modeling platform to answer the other three basic questions; that is to assess the role of wetlands on NBS, flows, and water levels; the additional benefits of flooding farmland and the effect of additional wetlands on providing relief to floods. This platform was designed to simulate the effect of land cover on flows; delineating a watershed into river segments and hillslopes; providing input to a lake/reservoir water balance model or a hydraulic or hydrodynamic model to obtain the ensuing effects on water levels. The platform does not provide a hydraulic model in the true sense and, thus, cannot be used to build high-resolution flood inundated maps.

Using readily available data and PHYSITEL, the 23,799-km^2 LCRR basin was discretized into hillslopes (*i.e.*, computational units, a.k.a. RHHUs), namely 8473 RHHUs (avg. 2.81 km^2) and 3289 rivers & lake segments (avg. 2.81 km) (LC 170 km). The model was calibrated and validated with an extensive data set including 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 storage scenarios: (i) conversion of agricultural land to « wetlands » within a 1000-m buffer zone along the entire river network of the LCRR basin (2812 km^2; 2471 km^2 RR (Fryer); 2256 km^2 LC) using the isolated and riparian wetland modules of HYDROTEL; (ii) converting local topographic depressions into wetlands with different design criteria (e.g., threshold for storage capacity, wetland area (i.e., number of tiles converging towards the deepest tile) and drainage area (minimum number of tiles converging towards the wetland area) excluding actual wetlands, water, urban area and roads; (iii) addition of wetland areas on land naturally accumulating water due to topography and given poorly or very poorly drained soils using dataset produced by the USEPA to support research and online mapping activities related to the EnviroAtlas; and (iv) combining scenarios (ii) & (iii). The simulation results were analyzed in terms NBS (inflows from all sub-watersheds and hillslopes discharging into LC, + precipitation and evaporation); flows (annual and seasonal high flows and 7-day low flows) and water levels in LC and the RR at the St. Jean Marina (NBS as input to the daily LC water balance model (WBM) developed by Environment and Climate Change Canada, ECCC).

The results of this study clearly quantified the hydrological services provided by the actual 1684 km^2 of wetlands (7% of the basin area draining 34% of the basin area) and illustrated their key role currently played in the attenuation of NBS, peak flows, and water levels, especially during the 2011 flood as well as the breath of their theoretical effect when using 64 years of meteorological data. The four watershed storage scenarios (corresponding to additional storage areas of 2256 km^2 of potentially flooded farmland, and 647 km^2, 865 km^2 and 1488 km^2 of wetlands) highlighted the potential of achieving additional gains to reduce LC NBS and water levels and to a lesser extent RR peak flows and water levels. Adding wetlands and/or potentially flooding farmland would require extensive surface area requirements. Given existing policies, programs and regulations North (e.g., Quebec Bill 132 - An

Act respecting the conservation of wetlands and bodies of water) and South (e.g., programs managed by the USDA Natural Resources Conservation Service and the USDA Fish and Wildlife Service, and Vermont and New York States Departments of Environmental Conservation) of the boarder, fostering restauration and construction of wetlands, might provide a socially-acceptable framework to build resilience over time in the LCRR basin, at least at the local sub-watershed level. 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. In addition, the LCRR HYDROTEL modelling project is available to assess multiple scenarios for each sub-watershed, but ultimately for any scenario, there is need to conduct comprehensive studies, including: (i) 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 « *x* » and « *y* » cm in LC and RR, respectively; (ii) an assessment of the effect on low flows; and (iii) a cost-benefit analysis including total costs (e.g., construction, easement payments, …) and total benefits (e.g., avoided damages, valuing environmental goods and services…).

It is noteworthy, the outcomes of this study were presented at two IJC technical webinars held on November 5, 2020.

1 Introduction

The Richelieu River (RR) and Lake Champlain (LC) sub-watersheds make up the Lake Champlain-Richelieu River (LCRR) watershed. The RR sub-watershed contributes to roughly 10% of the annual discharge into the St. Lawrence River; while the total discharge flowing out of the Lake Champlain 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 precipitations in April and May 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 Lake Champlain and along the Richelieu River suffered considerable economic losses; with 79%, 10% and 11% of the losses occurring in Québec, Vermont and New York, respectively.

In a general manner there exist two approaches to flood mitigation for protecting critical areas in the LCRR watershed: (i) allowing water to naturally overflow on dedicated landscapes as stage rises above the river banks or shorelines (i.e., passive storage); and (ii) directing water through the use of gates, dykes, 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). Construction or restoration of wetlands on the LCRR landscapes can be seen as a passive storage approach to reduce both high flows (e.g., Fossey et al., 2016a,b,c) and to a lesser extent flood volumes (e.g., Blanchette et al., 2019). When both aforementioned approaches are considered, the active one compliments the passive one.

2 Objectives and tasks

The main objective of this study was to assess the effect of passive and active approaches of flood mitigation methods in the LCRR watershed; that is assessing the potential: (i) attenuation of high flows provided by current, restored, and constructed wetlands of tributaries of the watershed and (ii) storage of flood water on riparian agricultural landscapes. The second 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, it might be better to referred to this approach as a pseudo-active approach.

Completed 2019-2020 tasks

Here is a brief description of the tasks completed during the September 2019 to November 2020 period.

1. Analysis of an existing PHYSITEL/HYDROTEL project supported by FMMM[1], 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.

[1] 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).

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.

3 Material and methods

This project was supported by seven (7) major work packages namely:

(i) Adapting the current implementation of HYDROTEL on LCRR watershed - supported by the FMMM group - along with all datasets used to develop an updated watershed database using PHYSITEL and achieve a current hydrological modelling of the LCRR watershed. 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 precise data.

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

(iii) Construction of a scenario focussing on storing flood water on riparian agricultural landscapes using stream network and agricultural field proximity.

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

(v) 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 scenario for all the major tributaries of the LCRR sub-watersheds.

(vi) 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 scenario on Lake Champlain water level and Richelieu River flows.

(vii) 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 watershed and mapping using PHYSITEL potential areas to store water away from areas to be protected.

4 Data collection/transfer and processing using PHYSITEL

At the beginning of the project we inquired to the DEHAQ (*Direction de l'expertise hydrique et atmosphérique du Ministère de l'Environnement et la Lutte au changement climatique*) about their contribution to the aforementioned FMMM project. Indeed, the DEHAQ had built the PHYSITEL/HYDROTEL LCRR project that was used by researchers at ÉTS (*École de Technologie Supérieure*) who were in charge of the simulation of the multi-year mean annual hydrograph and 2011 flood of the LCRR basin. Hence, the DEHAQ transferred us the watershed limits, hydrographic network, and hydrometeorological database. Instead of using their 100-m spatial resolution, we elected for a 30-m horizontal resolution to take advantage of the readily available and higher resolution land cover and wetland maps.

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. Additional characterization of the watershed 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 watershed 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 watershed maps of the input data introduced in Table 4.1.

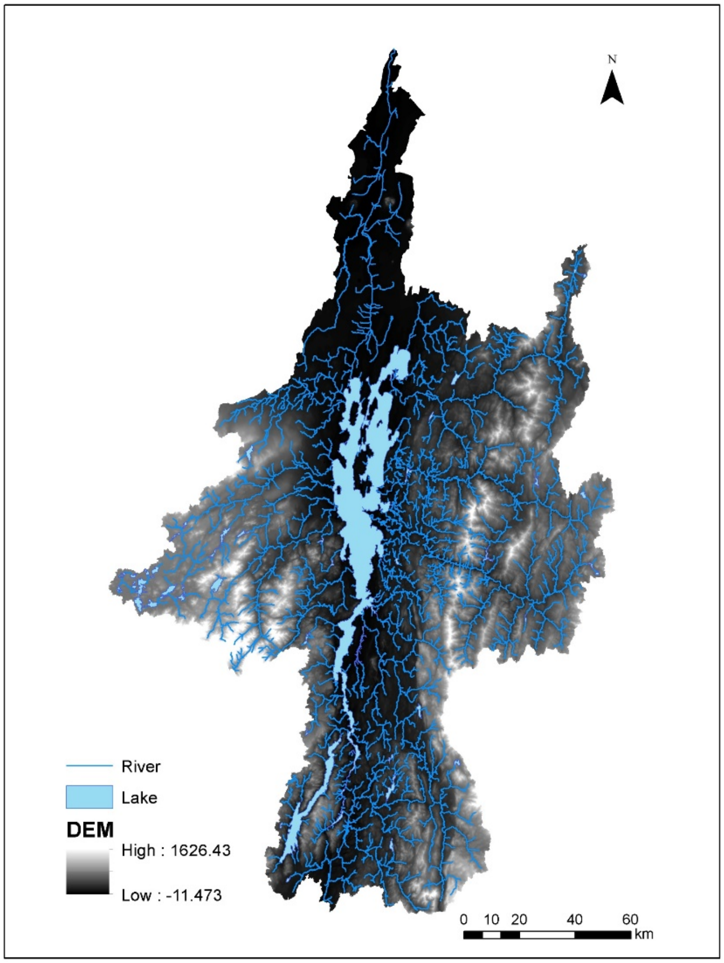


Figure 4.1 Digital elevation model (DEM) and stream and lake network.

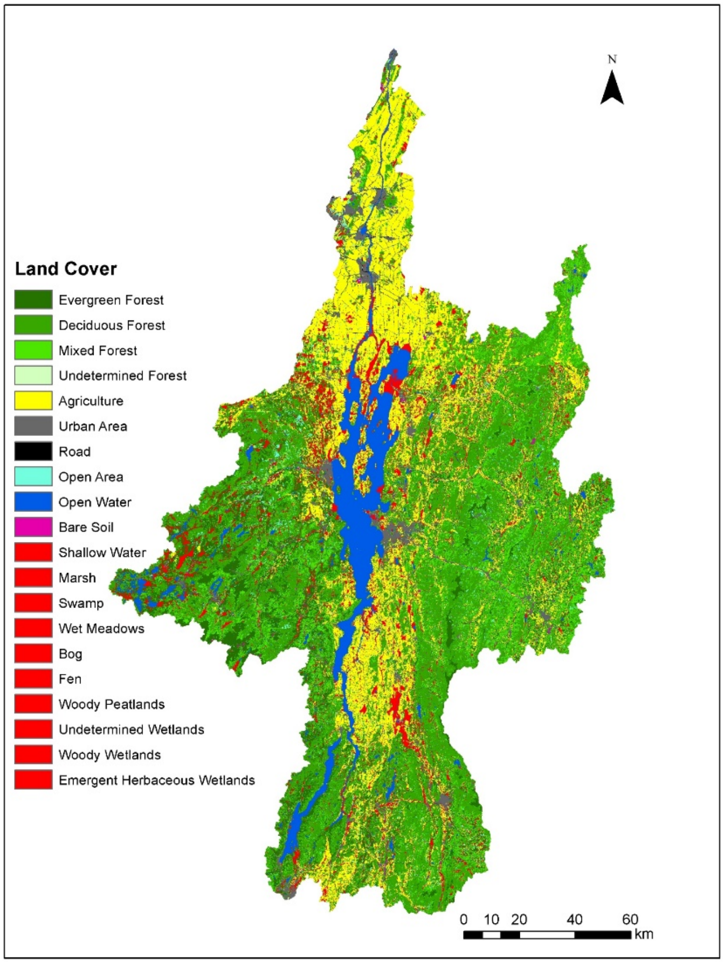


Figure 4.2 Land cover and wetlands inventory.

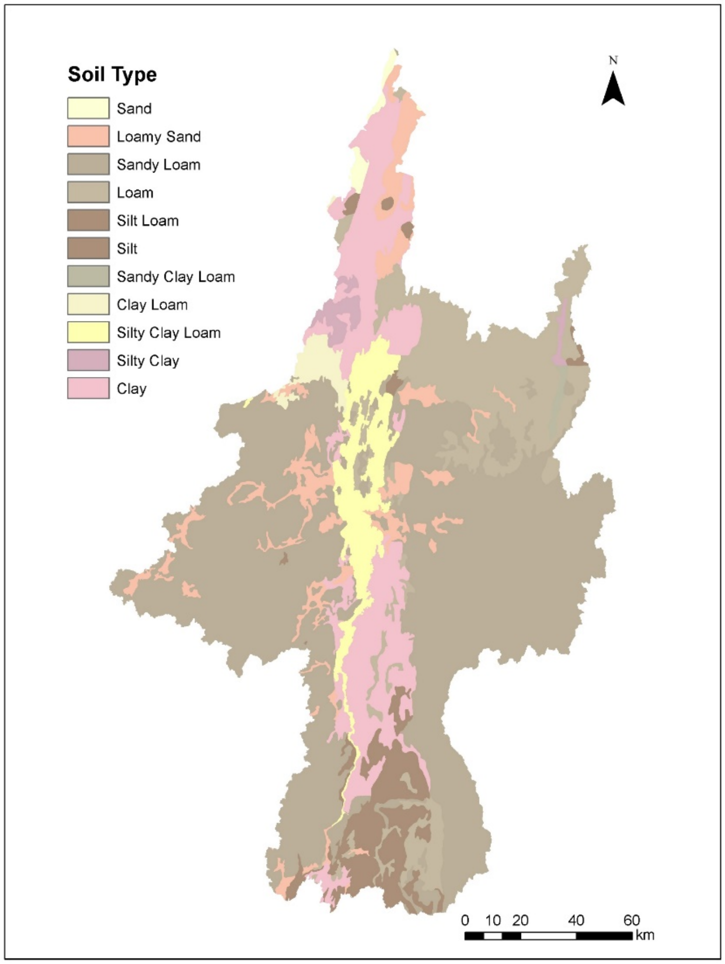


Figure 4.3 Soil type.

Additional data requirement for hydrological modelling included: (i) meteorological data measured at existing stations or reconstructed and distributed on a grid; (ii) measured streamflow data at any location on the stream network or reconstructed reservoir/lake inflows.

Given the aforementioned geographic data, PHYSITEL was used to delineate the watershed into Relatively Homogenous Hydrological Units (i.e., namely hillslopes, a.k.a, RRHU) and river/lake segments which made up the computational domains of HYDROTEL. In other words, PHYSITEL determines the internal drainage structure (slopes and flow directions), watershed boundaries, sub-watershed and hillslope boundaries, and hydrographic network. 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.

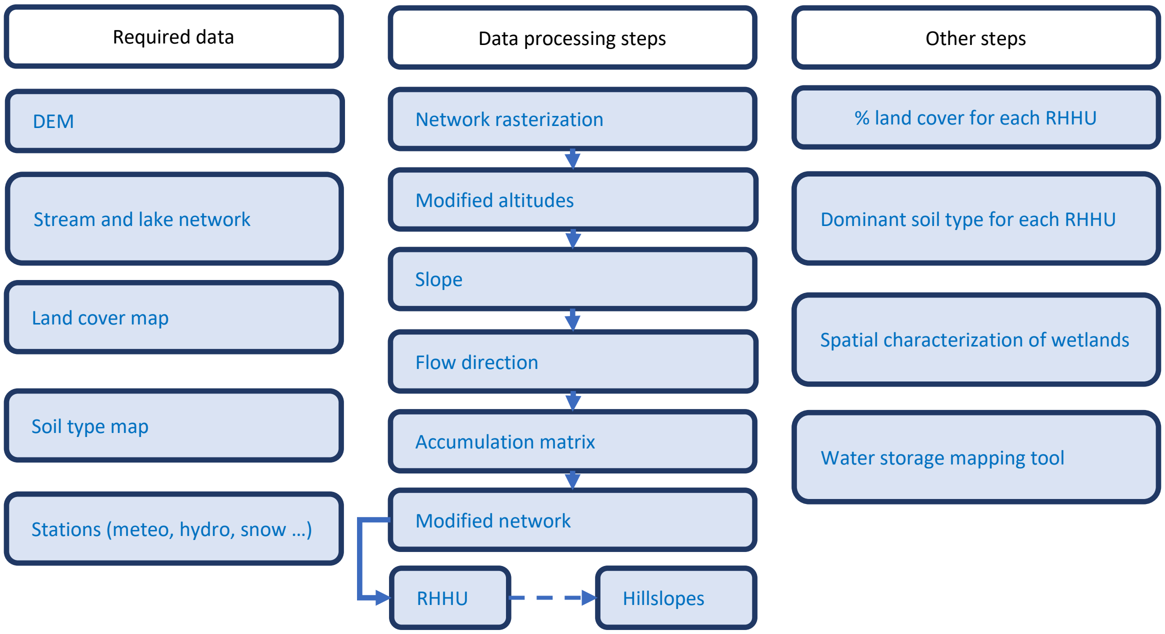


Figure 4.4 PHYSITEL – Input data and data processing.

As indicated, PHYSITEL allowed for the spatial characterization of wetlands based on the available types of wetlands (see Figure 4.2) provided by the land cover map. In addition, PHYSITEL delineated isolated and riparian (based on a river connectivity threshold) wetlands and corresponding drainage areas.

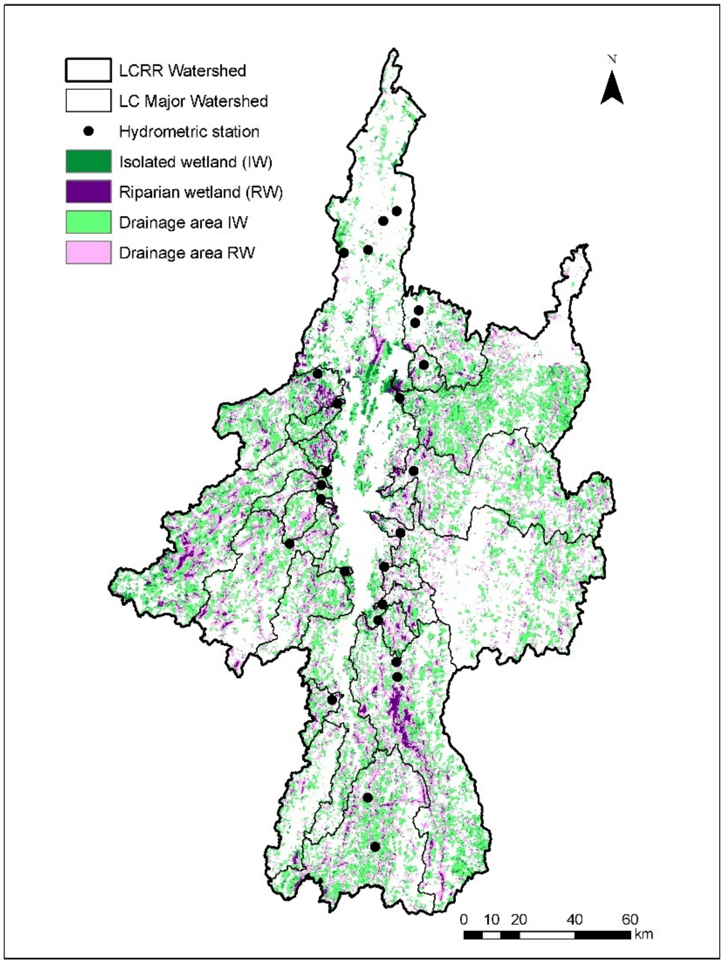


Figure 4.5 Drainage area and types (isolated and riparian) of wetlands in the LCRR watershed.

As a complement, Table 4.2 summarizes the cumulative drainage area of each type of wetlands within the LCRR and Lake Champlain (LC) watersheds.

Table 4.2 Drainage area and surface area of each type of wetlands within the LCRR and Lake Champlain (LC) watersheds.

	Area (km²) (fraction of the watershed)	
Watershed	LCRR	LC
Total watershed	23799 km^2	21254 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)	1684 km^2 (7%)	1551 km^2 (7%)
Drainage area IW	5537 km^2 (23 %)	5254 km^2 (25 %)
Drainage area RW	2561 km^2 (11 %)	2495 km^2 (12 %)
Total drainage area	8099 km^2 (34%)	7749 km^2 (37%)

It is noteworthy that, in terms of total watershed area, the cumulative surface area and drainage area of wetlands of the LC and LCRR watersheds are 7% and 34%, respectively; also 92% of wetlands are located within the USA. It is noteworthy that the drainage area does not include the wetlands area. This table highlights that even a small coverage of wetlands can drain a large fraction of a watershed. Section 6 presents a detailed table on wetland area and drainage area for all major LCRR major sub-watersheds.

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 using a daily time step for this study: the spatial distribution of meteorological conditions, evapotranspiration, snow accumulation/melt, infiltration, recharge, surface flow, subsurface flow and channel routing.

HYDROTEL provides 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 I or if needed the reader should 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.

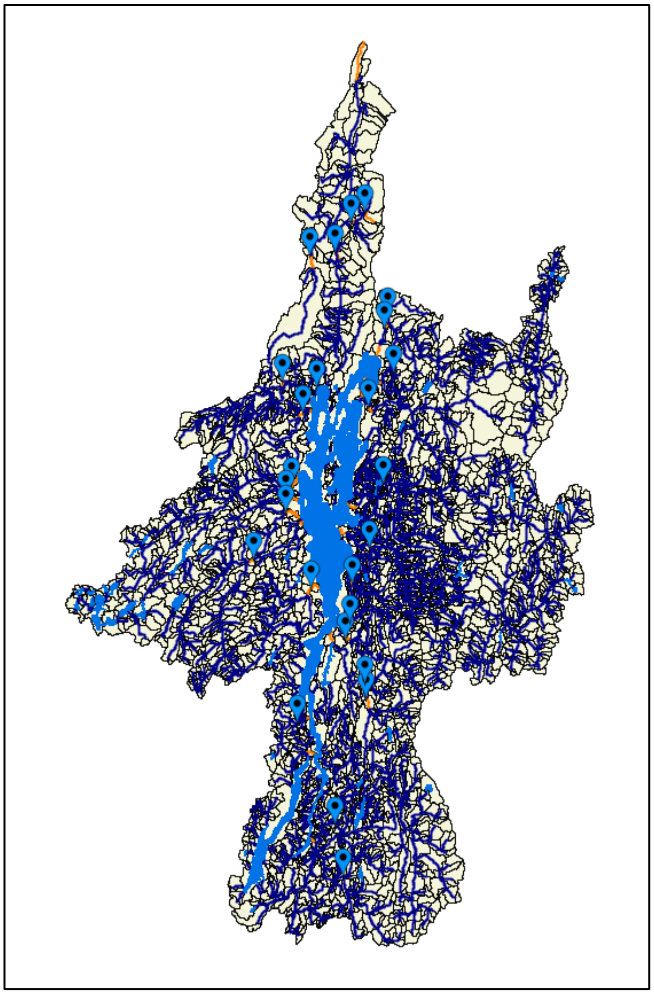


Figure 5.1 LCRR project of HYDROTEL.

For this study, the LCRR was delineated into 8473 RHHUs (i.e., hillslopes; avg. 2.81 km²) and 3289 river & lake segments (avg. 2.81 km N.B. LC 170-km long); that is the hydrological computational domain.

Hydrologic simulations were driven by gridded meteorological conditions from 1950 to 2013 (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 DEHAQ, 1 FGC) within the LC sub-watershed and LCRR watershed. Quarter monthly net basin supply (NBS) were also available for Lake Champlain. Even if HYDROTEL was calibrated to corroborate as well as possible the flows of the Richelieu River (*Aux Rapides Fryers*) recorded at the Canadian Government Hydrometric Station (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. Calibration was performed in a distributed fashion to represent flow observations as well as possible. For most of the sub-watersheds, calibration was performed independently; meanwhile for the calibration of the most downstream river segment, the calibration benefited from the upstream calibrated sub-watersheds. In order to assess and illustrate the impacts of all water storage scenarios on the worst known hydrological year, a specific calibration was 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 sub-watershed (at the hydrometric station site) were found using the Kling-Gupta Efficiency criterion (KGE) (Gupta et al., 2009) as a first performance indicator and the mean squared error (MSE) as a 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. As mentioned before, the calibration was performed to corroborate as well as possible the flows measured at Rapid Fryers, 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.

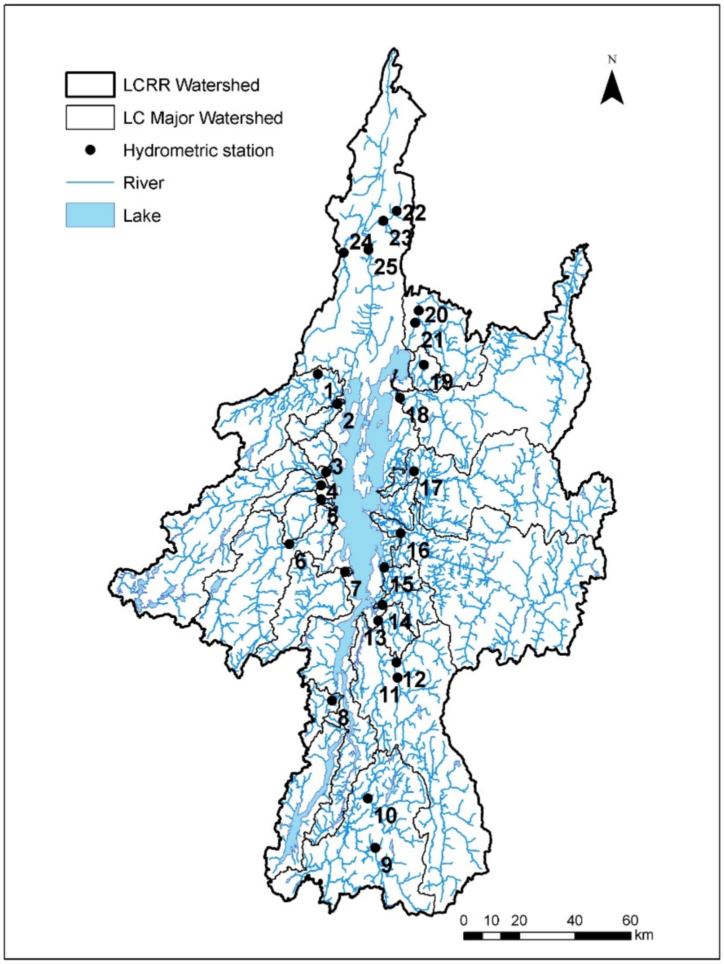


Figure 5.2 Location of the 25 hydrometric stations within the LCRR watershed.

Table 5.1 HYDROTEL calibration and validation results.

#	STATION	WATERSHED	DRAINAGE (km²)	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
		MEAN			0.82		0.76
25	***0030401***	***RR (FRYERS)***	***22054.83***	***1992-2003***	***0.88***	***2004-2013***	***0.92***

For most of the sites and sub-watersheds with observations, results are deemed satisfactory, nonetheless the large sub-watersheds 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 going from 082 to 0.76). For the SALMON, LITTLE AUSABLE, DE LA ROCHE and À L’OURS sub-watersheds, the performance decreases more drastically for the validation period while for other sub-watersheds 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, are 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: (i) , the sum of observations, namely sub-watersheds 1 to 18 as identified on Figure 5.2; which essentially corresponds to majors flows entering Lake Champlain (see first rows of Figure 5.3 and Figure 5.4); (ii) an estimation of the Lake Champlain net basin supply (NBS) 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). The NBS is made of inflows from all rivers discharging into Lake Champlain, precipitation over the lake, and lake evaporation and (iii) as a complement a comparison of simulated and observed Richelieu River flows, downstream of Lake Champlain, *Aux Rapides Fryers* (Rapid Fryers station) hydrometric station (see last rows of Figure 5.3 and Figure 5.4) based on the official daily Lake Champlain Water Balance Model (WBM) using HYDROTEL NBS as input.

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

(b) Lake Champlain NBS

(c) River flows at Fryers

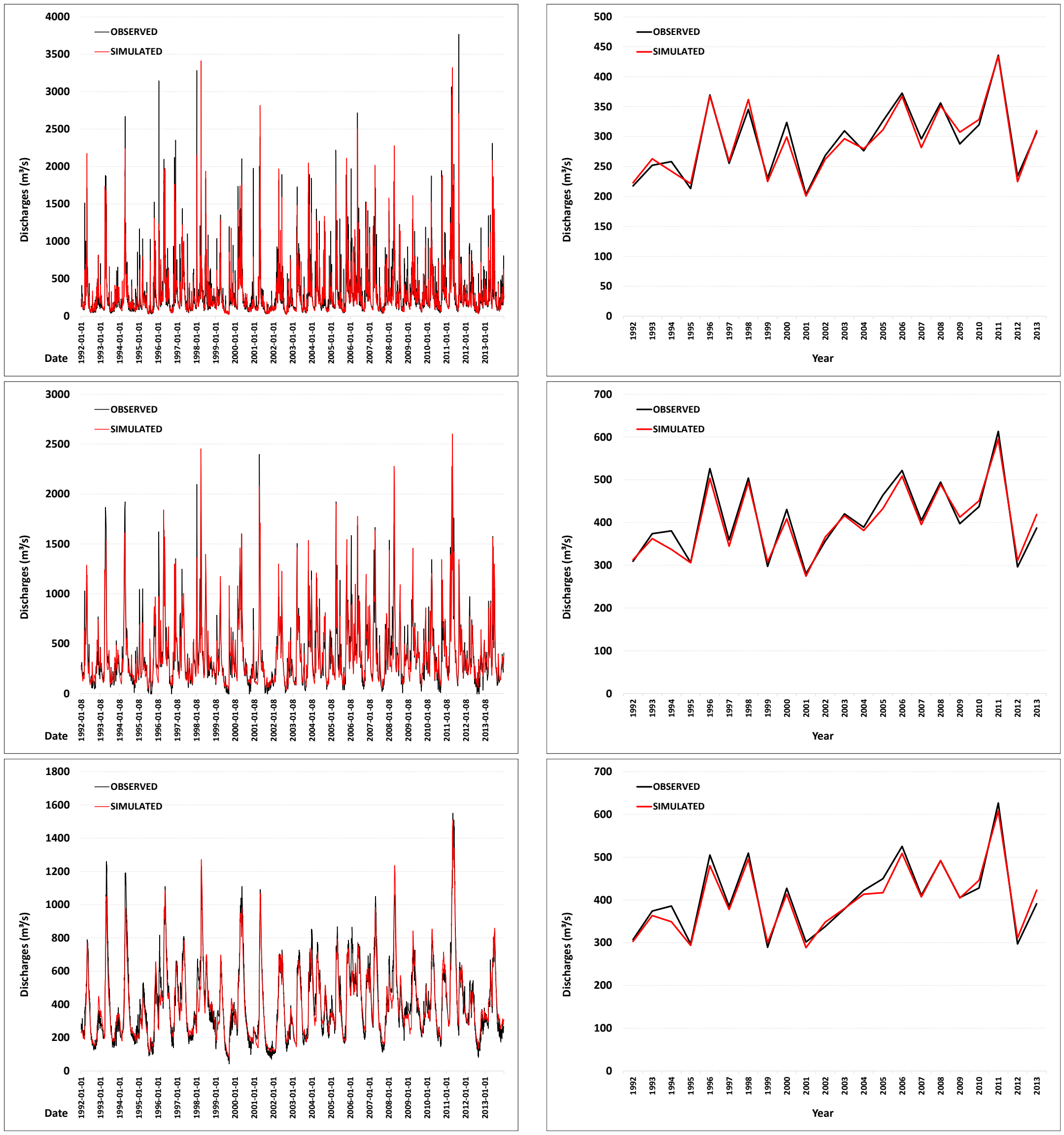


Figure 5.3 Daily (left column) and annual (right column) time series (1992-2013) of the sum of the river flows of the 18 Lake Champlain sub-watersheds (a), the Lake Champlain Net Basin Supply (NBS) (b) and the Richelieu River flows at Rapid Fryers station (c). Observations are displayed in black and simulations in red.

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

(b) Lake Champlain NBS

(c) River flow at Fryers

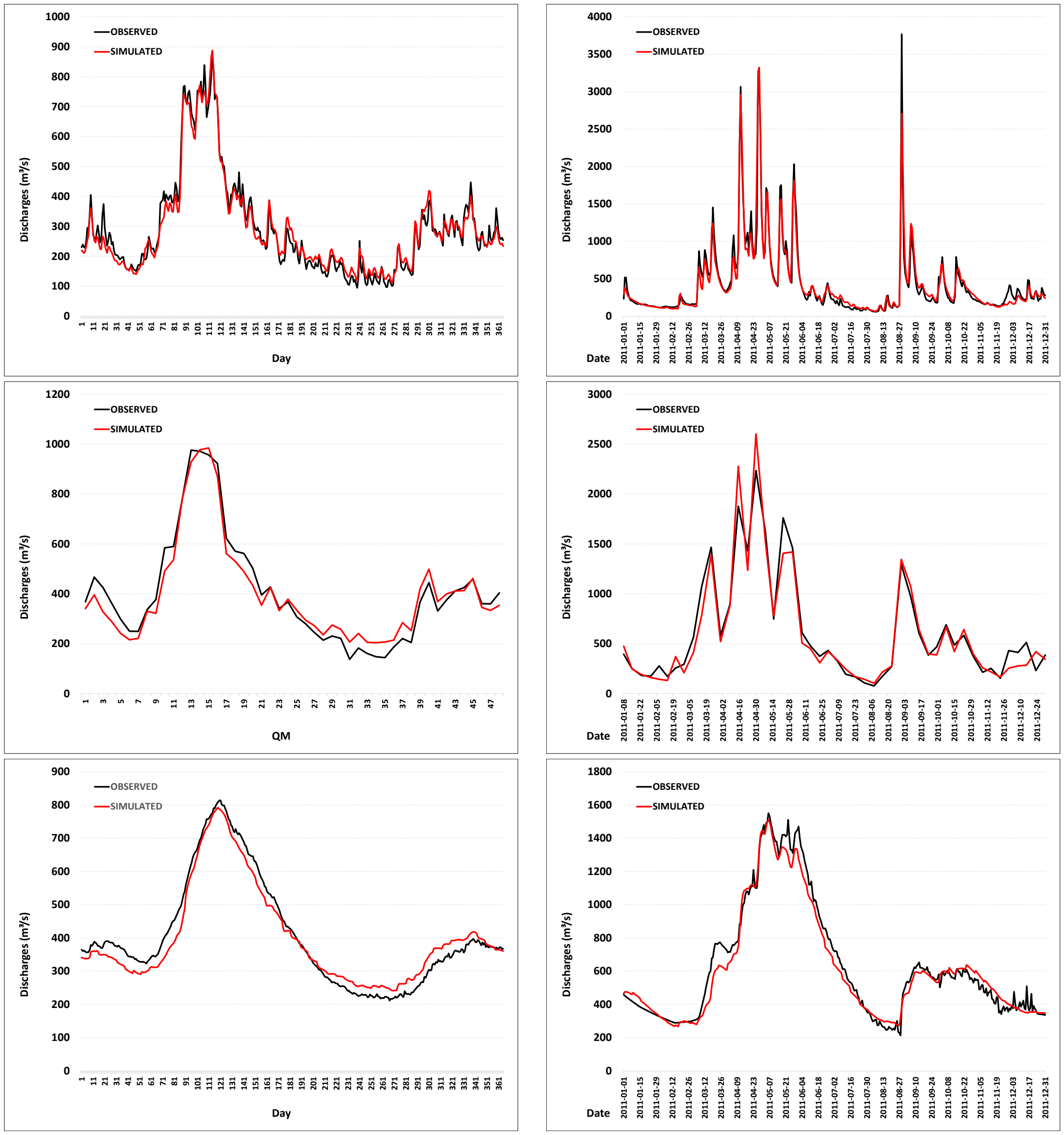


Figure 5.4 1992-2013 average annual hydrograph (left column) and 2011 hydrograph (right column) of the sum of river flows of the 18 gauged Lake Champlain sub-watersheds (a), the of Lake Champlain Net Basin Supply (NBS) (b) and the Richelieu river flows at Rapid Fryers station (c). Observations are displayed in black and simulations in red.

Looking at the 1992-2013 time series of the rivers flows of the 18 Lake Champlain sub-watersheds (referred to as sum-18 (top left graph of Figure 5.3), a consistent pattern with a maximum in spring and minimum in summer can be seen. 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 sub-watersheds 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 corresponding to 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, 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 KEG 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, also 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.

To complete the analysis, the simulated and observed Richelieu River flows, downstream of Lake Champlain, at Rapid Fryers 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 Rapid Fryers 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 1550 m^3/s by 40 m^3/s in early May at Rapid Fryers station. Simulated flows at Rapid Fryers station remains a challenge due to the upstream Lake Champlain water storage and routing effect. This is the official results for the Richelieu River based on the HYDROTEL NBS as input to the daily Lake Champlain WBM; that is the specific and official model for this water regime in the LCRR watershed.

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

Wetlands are natural landscape features within a watershed. Located at the interface between terrestrial ecosystems and water resources such as water courses and shallow water tables, they 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 regulations as highlighted by amplifying low flows and attenuating high flows.

Existing wetlands within the LCRR watersheds provide hydrological services that need to be quantified. The evaluation of these services become highly relevant to stakeholders involved in water resources management and wetlands protection/conservation programs. Over the past 5 years, the wetland modules available in HYDROTEL have been used extensively by our research group (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 I.

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, we used a simple comparison approach based on two distinct hydrological simulations: (i) one with the wetland modules turned on and (ii) another one 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 to isolate 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: $(Without\ Wetlands - Current\ Wetlands)/Without\ Wetlands$ where a positive result corresponds to a high flow attenuation.

For low flows: $(Current\ Wetlands - Without\ Wetlands)/Without\ Wetlands$ where a positive result corresponds to a low flow amplification.

To quantify the high flow attenuation services, we calculated, based on a continuous with- and without wetland long term hydrological simulation covering years 1950 to 2013, the relative variation on annual, spring and fall maximum flows; while the low flow amplification services were assessed by calculating the relative variation on annual, spring and fall minimum 7-day low flow. 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 sub-watersheds of the LC watershed while Table 6.1 introduces for every sub-watersheds, the wetland area and associated drainage area. Figure 6.2 highlights the impact (annual, spring, summer/fall) of the current distribution of wetlands on high flows. As this study emphasis more specifically high flows and flood risk, the impact of the current distribution of wetlands on low flows are reported in Appendix II (Figures A 2-4). Table 6.2 summarizes the annual impact of current wetlands on high flows for the 20 major LC sub-watersheds, LC NBS, RR flows at Rapid Fryers and the 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.

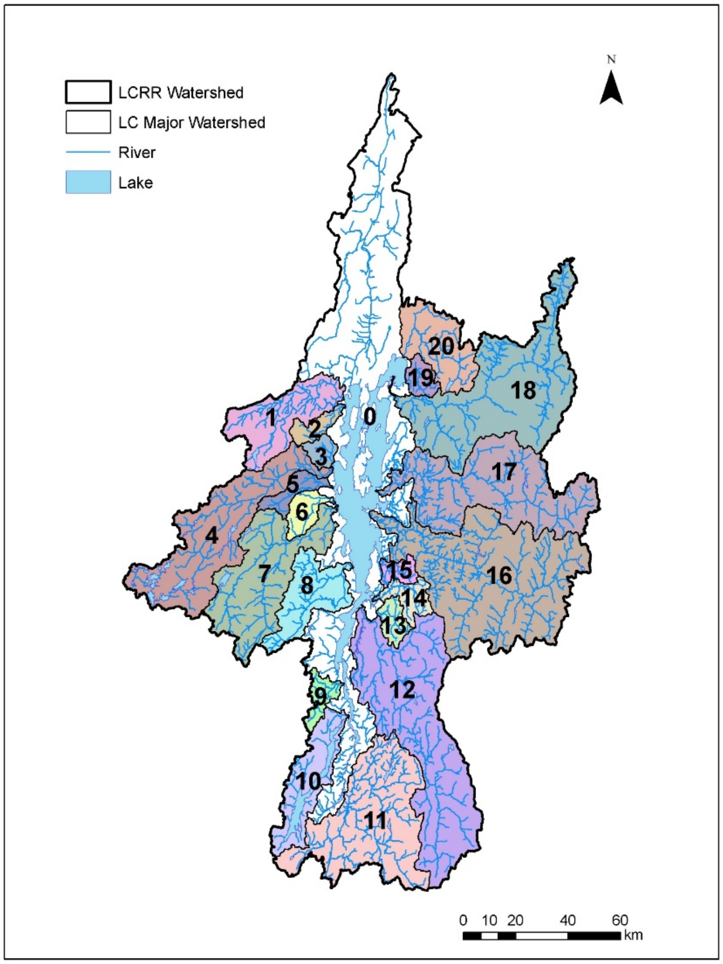
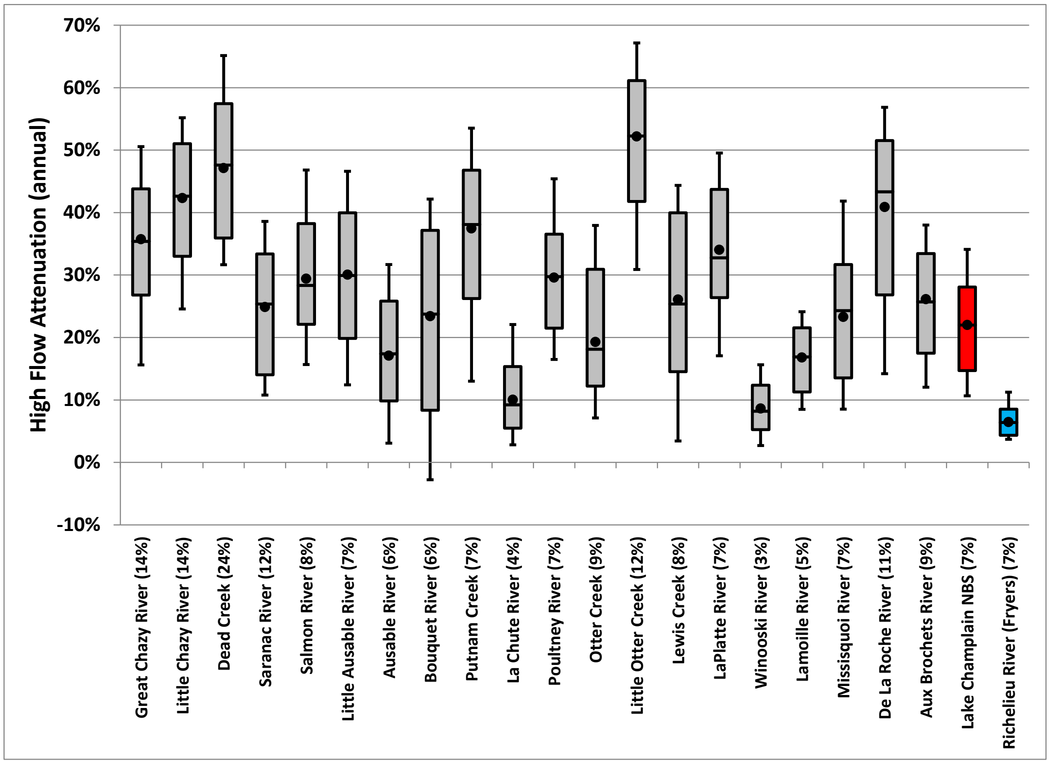


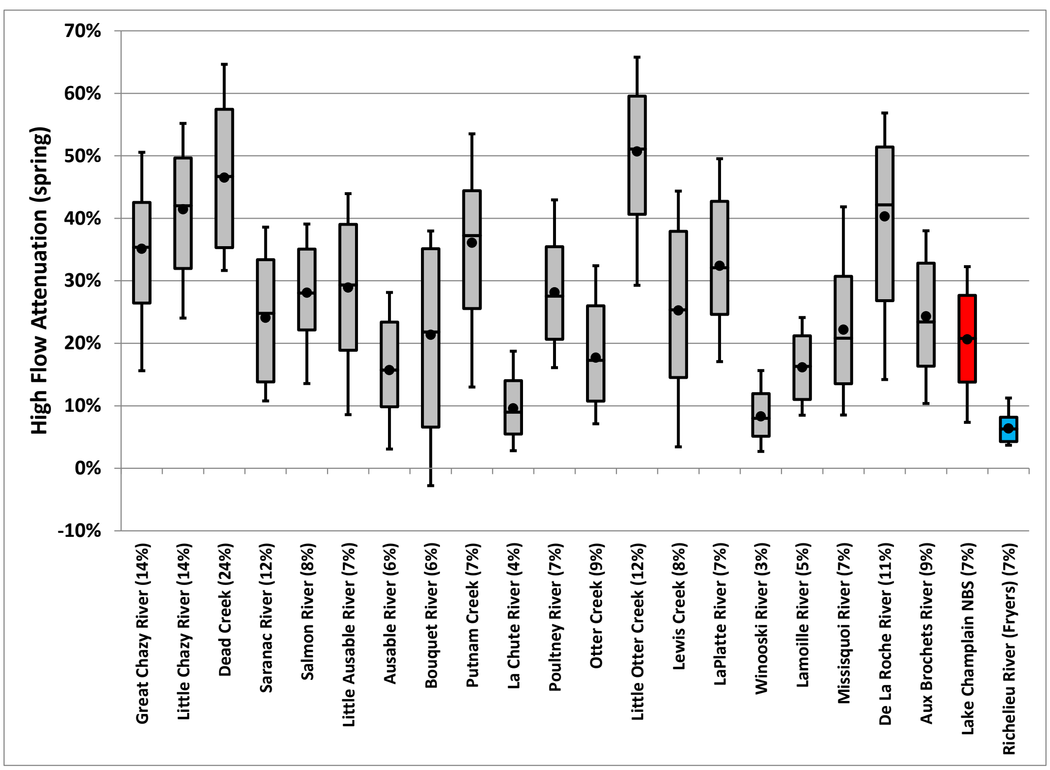
Figure 6.1 Major LC sub-watersheds (>100 km²).

Table 6.1 Description of wetlands area and wetlands drainage area for the 20 LC sub-watersheds, LC and RR flows at Rapid Fryers watersheds.

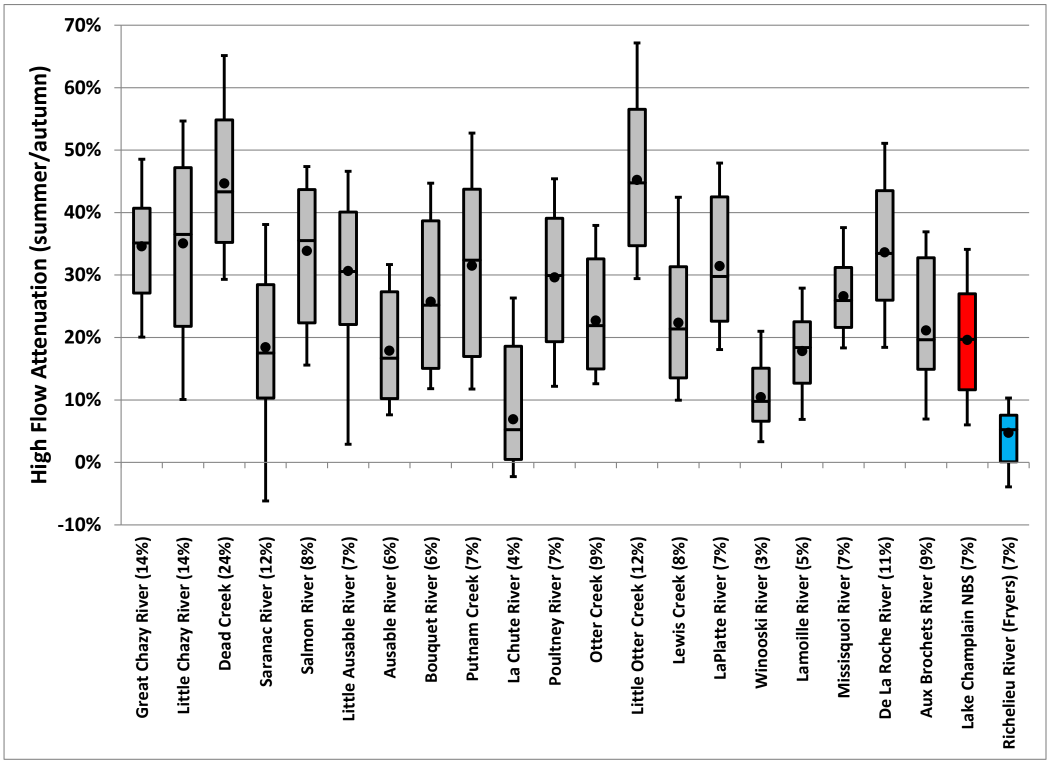
#	WATERSHED	DRAINAGE (km²)	WETLANDS		WETLANDS DRAINAGE	
			(km²)	(%)	(km²)	(%)
1	Great Chazy	778	107	13.8%	371	47.6%
2	Little Chazy	143	20	14.2%	73	50.9%
3	Dead Creek	114	27	24.0%	63	55.3%
4	Saranac	1579	184	11.6%	761	48.2%
5	Salmon	177	15	8.3%	90	51.0%
6	Little Ausable	188	13	6.7%	94	50.2%
7	Ausable	1329	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	1778	120	6.8%	775	43.6%
12	Otter Creek	2446	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	2756	79	2.9%	658	23.9%
17	Lamoille	1866	94	5.0%	707	37.9%
18	Missisquoi	2212	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	**21254**	**1551**	**7.3%**	**7749**	**36.5%**
	RR (Fryers)	**22055**	**1616**	**7.3%**	**7902**	**35.8%**


70%
60%
50%
40%
30%
20%
10%
0%
-10%
High Flow Attenuation (annual)
Great Chazy River (14%)
Little Chazy River (14%)
Dead Creek (24%)
Saranac River (12%)
Salmon River (8%)
Little Ausable River (7%)
Ausable River (6%)
Bouquet River (6%)
Putnam Creek (7%)
La Chute River (4%)
Poultney River (7%)
Otter Creek (9%)
Little Otter Creek (12%)
Lewis Creek (8%)
LaPlatte River (7%)
Winooski River (3%)
Lamoille River (5%)
Missisquoi River (7%)
De La Roche River (11%)
Aux Brochets River (9%)
Lake Champlain NBS (7%)
Richelieu River (Fryers) (7%)

(a)


70%
60%
50%
40%
30%
20%
10%
0%
-10%
High Flow Attenuation (spring)
Great Chazy River (14%)
Little Chazy River (14%)
Dead Creek (24%)
Saranac River (12%)
Salmon River (8%)
Little Ausable River (7%)
Ausable River (6%)
Bouquet River (6%)
Putnam Creek (7%)
La Chute River (4%)
Poultney River (7%)
Otter Creek (9%)
Little Otter Creek (12%)
Lewis Creek (8%)
LaPlatte River (7%)
Winooski River (3%)
Lamoille River (5%)
Missisquoi River (7%)
De La Roche River (11%)
Aux Brochets River (9%)
Lake Champlain NBS (7%)
Richelieu River (Fryers) (7%)

(b)



(c)

Figure 6.2 Impacts of current wetlands on high flow attenuation (annual, spring, summer/fall) of the 20 LC sub-watersheds, LC NBS and RR flows at Rapid Fryers (Min; Max; 10th centile; 90th centile; Median; Average) for various temporal scales: (a) annual, (b) spring and (c) summer/fall.

Table 6.2 Impacts of current wetlands on high flows of the 20 LC sub-watersheds, LC NBS, RR flows at Rapid Fryers 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 sub-watersheds with a high percentage of the watershed drained by wetlands, we observed a significant impact on high flows when compared to large sub-watersheds with smaller percentage 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 sub-watershed. Moreover, it is consequent that annual impacts and spring impacts are similar as the highest flow occurs most of the time during the spring freshet. Figure 6.2 shows that for only one sub-watershed (Bouquet River), the annual or spring results include negative impacts (increase of high flows) and for two sub-watershed (Saranac and La Chute River) fall results include negative impacts. Table 6.2 shows variable maximum- or minimum-year impacts and clear 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 the damping effect of LC, wetlands still have a lingering effect and thus can reduce high flows by 6% on the Richelieu River at Rapid Fryers. These results clearly illustrate the high flow regulation services provided by the current distribution of wetlands in the LCRR watershed.

We also analysed how wetlands can affect flood in terms of four indicators, namely peak flow, mean flow, duration, and flow volume of high flow events. Then, we quantitatively assessed the effects during the rising and failing limbs of the event hydrograph to identify whether or not the services were altered. A 2-year return high flow threshold was taken to assess all indices, because it is often used as a proxy to bankfull discharge and threshold in other studies (Cheng et al., 2013; Xu et al., 2017). For each simulation year, if the daily flow was higher than or equal to the 2-years return flow (1950-2013), it was considered as a flood event depicted in time by when the flow exceeded the threshold and ending when flow recessed below the threshold (Figure 6.3). 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, we extracted the flood event lasting at least five days including or not the annual maximum peak flow (Figure 6.3). Simultaneously, the mean flow, duration and flow volume for the rising and falling limbs of the hydrograph were determined (Figure 6.3). Finally, the difference in the value of an indicator between for simulations with and without wetlands were calculated (Wu et al., 2020). Results related to flow or volume are presented as runoff (ratio of volume/ sub-watersheds area). To complete the analysis the occurrence of beneficial services were determined. In other words, over the entire flood events how often did the wetlands provide a positive service (high flow attenuation).

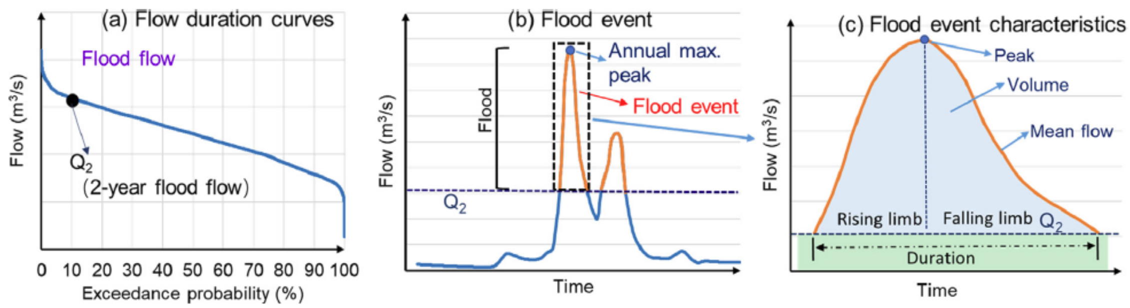


Figure 6.3 Methodology frame work used to (a) define high flow, (b) extract and (c) characterize flood events (taken from Wu et al., 2020).

Table 6.3 presents the impact of wetlands on high flow events while Table 6.4 presents the occurrence of attenuation.

Table 6.3 Median values of wetland impact on peak flow, flow duration, mean flow, and flow volume (i.e., runoff volume). D1 and D2 refer to the rising limb and failing limb of an event hydrograph, respectively (negative values corresponding to an attenuation).

#	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***

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%***

Table 6.3 clearly indicates that median values for peak flow, mean flow and volume are mostly reduced by existing wetlands for all sub-watersheds except for the rising limb volume indicator for the Lewis Creek sub-watersheds. Magnitude of reductions is related to the importance of the wetland 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 sub-watershed median duration in day are refers to attenuation, no effects or even amplification. Table 6.4 shows similar tendencies with important occurrence of flow and volume attenuation. Occurrence of attenuation on high flow events duration is less important, but small occurrence percentage does not correspond to high amplification percentage as no impact (0 day variation) neither lead to an 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.

6.1 Effect of current wetlands reported on the 2011 flood

In this section, Figure 6.4 presents the simulated 2011 hydrographs, but this time in terms of answering the following question: what would have been the impact of not having wetlands in 2011? Here 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.

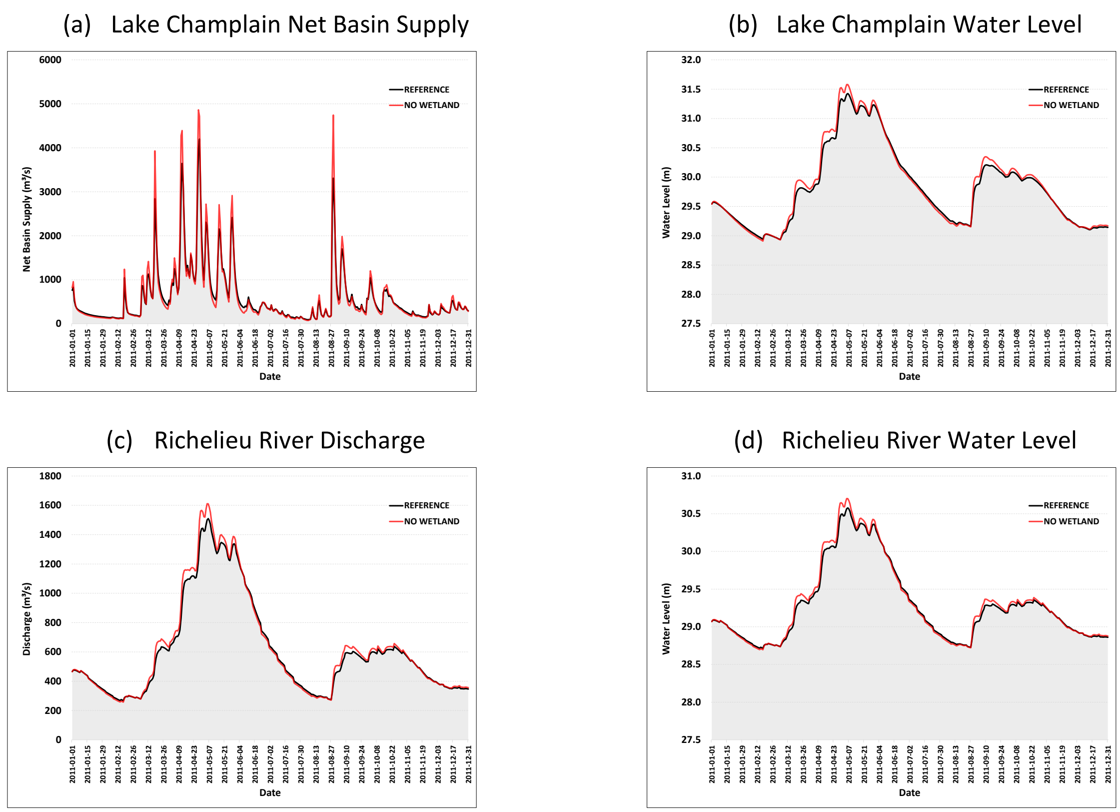


Figure 6.4 Impact of not having wetlands on NBS flows (a), LC water levels (b), discharges in the RR (c) at Rapid Fryers and RR water levels (Saint-Jean Marina) (d) given the 2011 conditions using HYDROTEL and WBM at a daily time step.

Table 6.5 summarizes the loss of wetlands scenario considering the 2011 conditions.

Table 6.5 Summary of not having wetlands on NBS flows, LC water levels, discharges in the RR at Rapid Fryers and RR water levels (Saint-Jean Marian) 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%)

Not having wetlands in 2011 would have made flooding conditions worse than those actually experienced. This substantiates the motivation behind the need to conserve and protect existing wetlands.

7 Learning from the 2011 flood

Using an educated approach, we can attempt to use the 2011 flood to come up with a few wetlands or flooded agricultural land scenarios. Based on flow measurements at the Richelieu River (*Aux Rapides Fryers*, Canadian Government Hydrometric Station number 02OJ007), we can estimate the amount of water that would need to be stored to reduce the 2011 peak flow by certain percentages and estimate thereafter the required surface area of additional wetlands or flooded farmland to store the water.

At first, in a simple fashion, the 2011 flood can be represented by a polynomial equation whereby the integral of measured flows or synthetic flood flows have identical volumes of water over a given time interval. Then it becomes an easy exercise to reduce the apex of the curves (synthetic flood) by 5%, 10% or 20%. Figure 7.1 provides an illustration of the simplified representation of the 2011 flows at the Rapid Fryers station from April 1st to July 3rd.

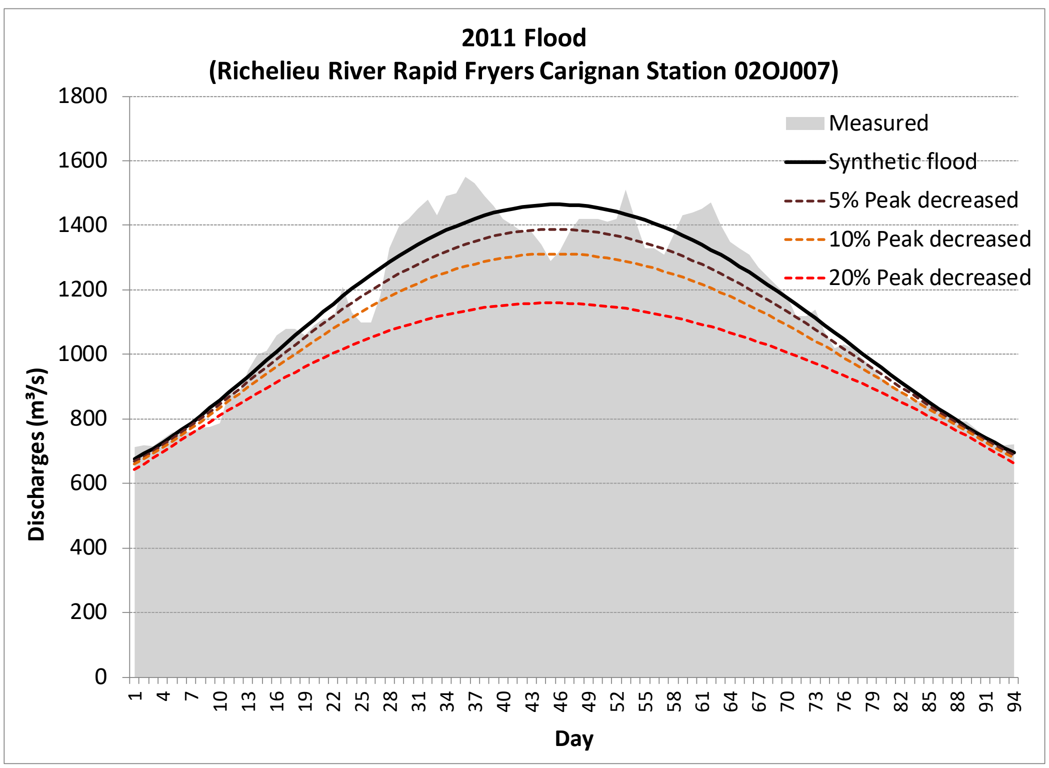


Figure 7.1 Simplified representations of the 2011 flood with a synthetic flood and ensuing shape of the flood given 5%, 10% and 20% reductions of the 2011 peak flow at the Rapid Fryers station from April 1st to July 3rd.

Table 7.1 Estimation of additional wetlands (area and % of increased compared to existing area of wetlands) or flooded farmland (in terms of % of existing farmland area) required to reduce the 2011 peak flow of the RR at Rapid Fryers assuming the additional storage areas would either store 50 cm or 10 cm of water.

50-cm water height	Wetlands	Increased (%)		Farmland Flooding (%)	
Peak reduction scenario	(km^2)	Upstream Fryers	LC Watershed	Upstream Fryers	LC Watershed
5%	632	39%	41%	17%	20%
10%	1263	78%	81%	34%	39%
20%	2527	156%	163%	68%	79%

10-cm water height	Wetlands	Increased (%)		Farmland Flooding (%)	
Peak reduction scenario	(km^2)	Upstream Fryers	LC Watershed	Upstream Fryers	LC Watershed
5%	3344	207%	216%	90%	104%
10%	6688	414%	431%	181%	209%
20%	13376	828%	862%	361%	418%

As introduced in Table 7.1, reducing the 2011 peak flow at Rapid Fryers by 5% would require an additional 632 km^2 of wetlands with a holding capacity of 50 cm of water which corresponds to increasing the surface area of wetlands by 39% upstream of the Rapid Fryers watershed or by 41% in the LC watershed. On the other hand, given the same water holding capacity, a 20% decrease in peak flow would require flooding 68% of existing farmland upstream of the Rapid Fryers 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 needed 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 10 cm. From a flood management perspective, this simple exercise allows us to appreciate the order of magnitude of required area to store water. It cannot in any case be considered as a hydrological modeling exercise.

The next chapters of the report focus on the evaluation of scenarios using HYDROTEL including wetland construction/restoration scenarios and a riparian agricultural land water storage scenario.

8 Evaluation of a riparian agricultural landscape water storage scenario

This scenario was meant to answer the following question: what would be the additional benefits of flooding farmlands? One way to develop this scenario was to treat agricultural land as if they were "wetlands", but without explicitly converting the farmland per say. It rather aimed at 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 » using the isolated and riparian wetland modules provided by HYDROTEL and assigning parameter values to farmland equivalent to those of existing and dominant wetlands within each computational unit (RHHU) or average parameter values (see Appendix I) 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 Rapid Fryers (from 1616 km² to 4087 km²) point including 2 256 km² within the boundaries of the Lake Champlain watershed (rom 1616 km² to 4087 km²). The 1-km buffer zone along the river network certainly represents an extensive area, although highly subjective the delineation of the buffer was meant to assess what would be the effect of storing water on an extensive area of farmland; acknowledging that in all likelihood the actual buffer zone would be smaller. It is noteworthy that further analyses could be done for a very large number of scenarios; that is specifically designed for each sub watershed, but given the allocated time to realize this project, it was beyond the scope. Figure 8.1 gives a general representation of the riparian agricultural landscapes water storage scenario.

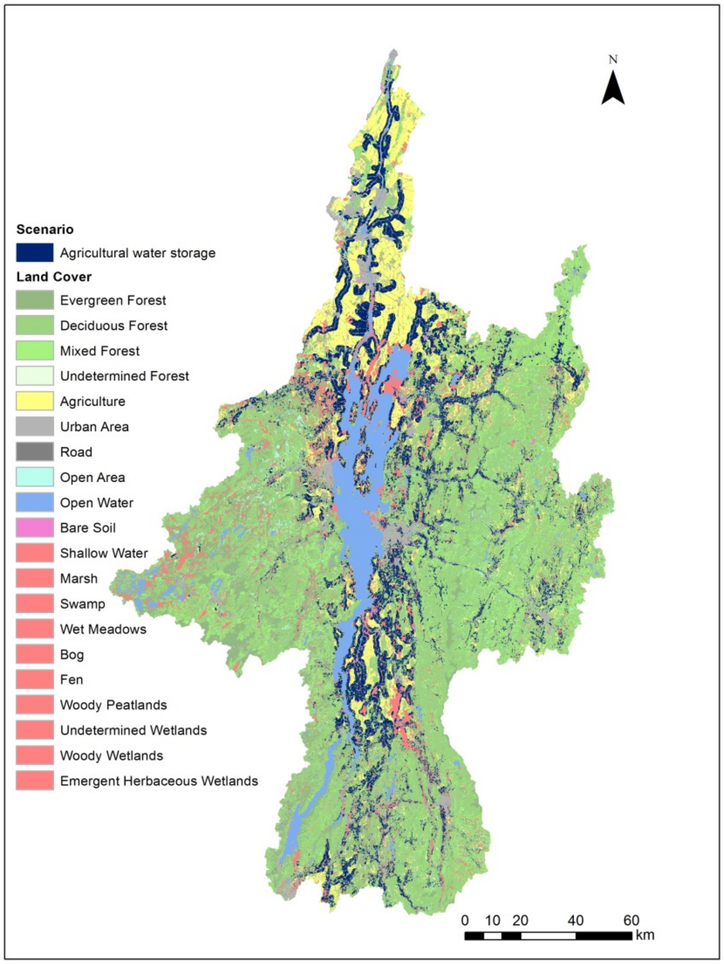


Figure 8.1 General representation of the riparian agricultural landscapes water storage scenario.

Table 8.1 describes for every sub-watersheds the impact of this water storage scenario on wetland and storage (i.e., farmland) areas as well as on their respective drainage area. A hydrological simulation for the 1950-2013 time period was performed using the additional storage area. Then high flow attenuation gain or low flow amplification gain were computed and to quantify the attenuation of high flows and amplification (a desirable effect) of low flows. The methodology is similar to the evaluation of the hydrological services provided by the current wetlands except that we are focusing on the gains compared to the current situation. The calculation procedure was as follows:

For high flows: $(Current\ Wetlands - Agricultural\ \ Scenario)/Current\ Wetlands$ where a positive result corresponds to an attenuation.

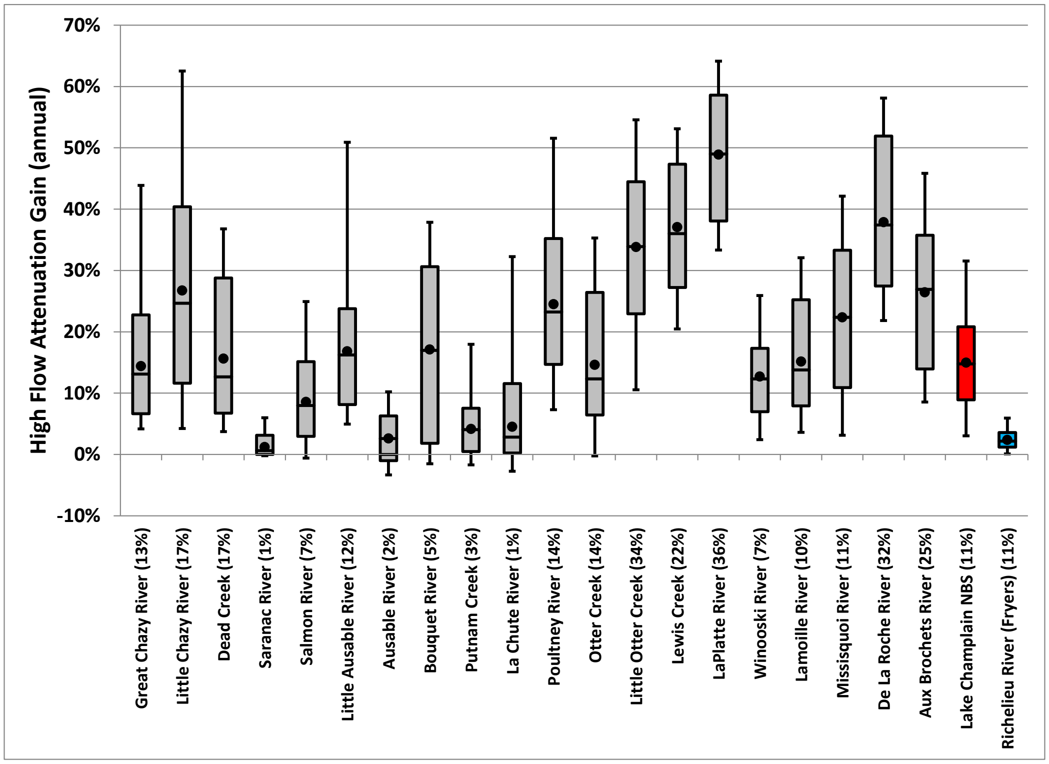
For low flows: $(Agricultural\ \ Scenario - Current\ Wetlands)/Current\ Wetlands$ where a positive result corresponds to an amplification.

Figure 8.2 highlights the effects (annual, spring, summer/fall) of the agricultural water storage scenario on the attenuation gain. As this study focuses more specifically on high flow and flood risk, the effect of the agricultural water storage scenario on low flows gain are reported in Appendix II (Figures A 5-7). Table 8.2 summarizes the annual effect on the attenuation gain for the 20 major LC sub-watersheds, LC NBS, RR flows at Rapid Fryers and water levels of the LC and RR (Marina Saint-Jean) based on the use of the NBS simulated by HYDROTEL as input to the daily Lake Champlain water balance model. Similarly to the results introduced in the previous Chapter, Table 8.2 includes also the effects for specific flood years.

Table 8.1 Spatial impact of storing water on riparian agricultural landscapes of the LCRR basin for the 20 LC sub-watersheds, LC NBS and RR flows at Rapid Fryers.

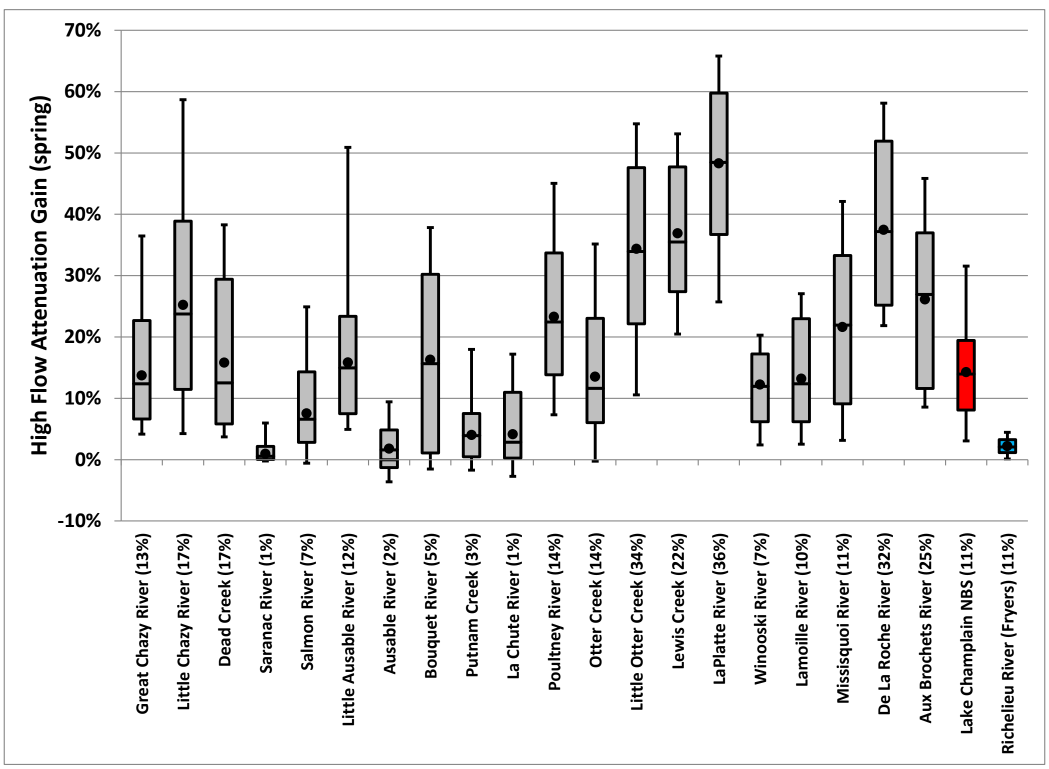
#	WATERSHED	DRAINAGE (km²)	Wetlands+Storage		vs. Watershed		W Drainage		vs. Watershed	
			(km²)	GAIN (km²)*	(%)	GAIN (%)*	(km²)	GAIN (km²)	(%)	GAIN (%)
1	Great Chazy	778	212	105	27.2%	13.5%	357	-14	45.9%	-1.7%
2	Little Chazy	143	45	25	31.5%	17.3%	69	-4	48.4%	-2.5%
3	Dead Creek	114	47	20	41.3%	17.3%	51	-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 Great Chazy with storing water on agricultural land we have 27.2% (13.8% of wetland land cover + 13.5% flooded farmland) of the watershed in storage area.



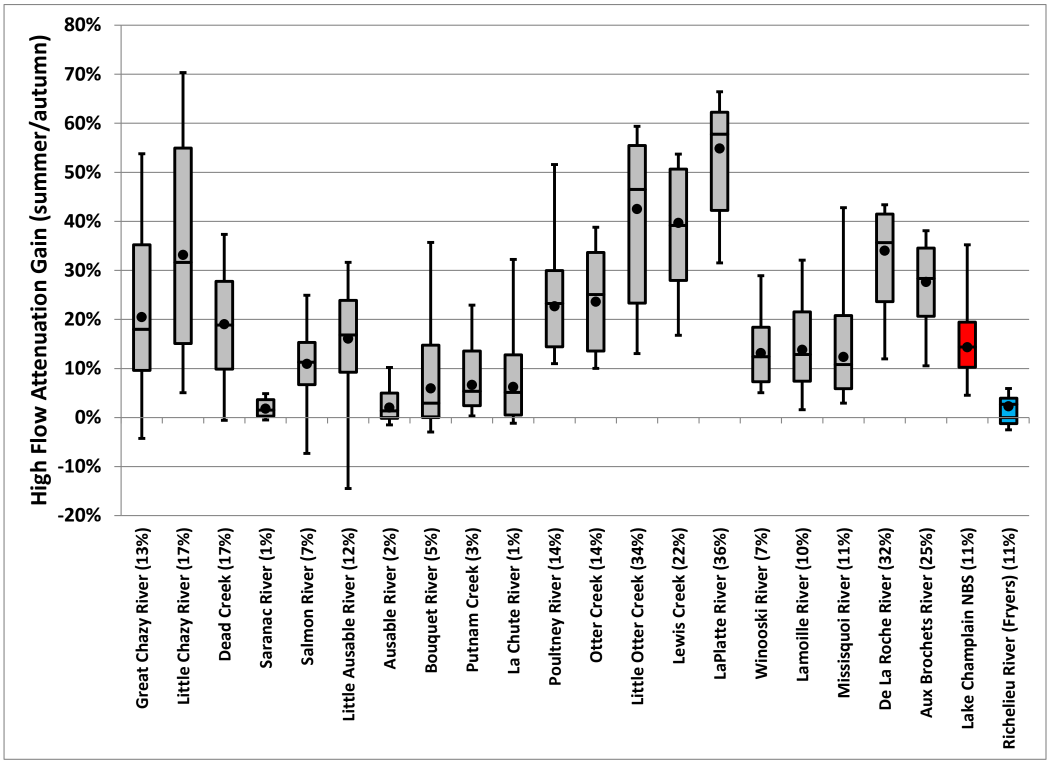
70%
60%
50%
40%
30%
20%
10%
0%
-10%
High Flow Attenuation Gain (annual)
Great Chazy River (13%)
Little Chazy River (17%)
Dead Creek (17%)
Saranac River (1%)
Salmon River (7%)
Little Ausable River (12%)
Ausable River (2%)
Bouquet River (5%)
Putnam Creek (3%)
La Chute River (1%)
Poultney River (14%)
Otter Creek (14%)
Little Otter Creek (34%)
Lewis Creek (22%)
LaPlatte River (36%)
Winooski River (7%)
Lamoille River (10%)
Missisquoi River (11%)
De La Roche River (32%)
Aux Brochets River (25%)
Lake Champlain NBS (11%)
Richelieu River (Fryers) (11%)

(a)



70%
60%
50%
40%
30%
20%
10%
0%
-10%
High Flow Attenuation Gain (spring)
Great Chazy River (13%)
Little Chazy River (17%)
Dead Creek (17%)
Saranac River (1%)
Salmon River (7%)
Little Ausable River (12%)
Ausable River (2%)
Bouquet River (5%)
Putnam Creek (3%)
La Chute River (1%)
Poultney River (14%)
Otter Creek (14%)
Little Otter Creek (34%)
Lewis Creek (22%)
LaPlatte River (36%)
Winooski River (7%)
Lamoille River (10%)
Missisquoi River (11%)
De La Roche River (32%)
Aux Brochets River (25%)
Lake Champlain NBS (11%)
Richelieu River (Fryers) (11%)

(b)



(c)

Figure 8.2 Gain in high flow attenuation due to storing water on riparian agricultural landscapes of the LCRR basin for the 20 LC sub-watersheds, LC NBS and RR flows at Rapid Fryers with respect to current conditions (Min; Max; 10th centile; 90th centile; Median; Average) 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 sub-watersheds, LC NBS, RR flows at Rapid Fryers 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***

Logically, for sub-watersheds with a high percentage gain of additional water storage area, we observe a significantly higher impact on high flows when compared sub-watersheds with smaller percentage gain. Figure 8.2 illustrates the impacts vary from year to year each sub-watersheds. 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 six (6) sub-watersheds (Saranac, Salmon, Ausable, Bouqet, Putman Creek, La Chute and Otter Creek), the annual or spring results can have negative impacts (increase of high flows) and for nine (9) sub-watersheds (Great Chazy River, Dead Creek, Saranac, Salmon, Little Ausable, Ausable, Bouquet, La Chute and Richelieu River (Fryers)), autumn results include negative impacts. Such negative values suggest that for a certain year, storing water on agricultural land could worsen the high flows. But is important to also to mention that all median or average attenuation gains are positive.

Table 8.2 indicates variable maximum or minimum year impacts and clear contribution of agricultural water storage for specific flood year (1973, 1983, 1984, 2011, and 2013). Based on the 1950-2013 meteorological conditions, large-scale storing of water on riparian agricultural landscapes can provide relief; 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 Rapid Fryers 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.

8.1 Effect on the 2011 flood

In this section, we focus 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 input.

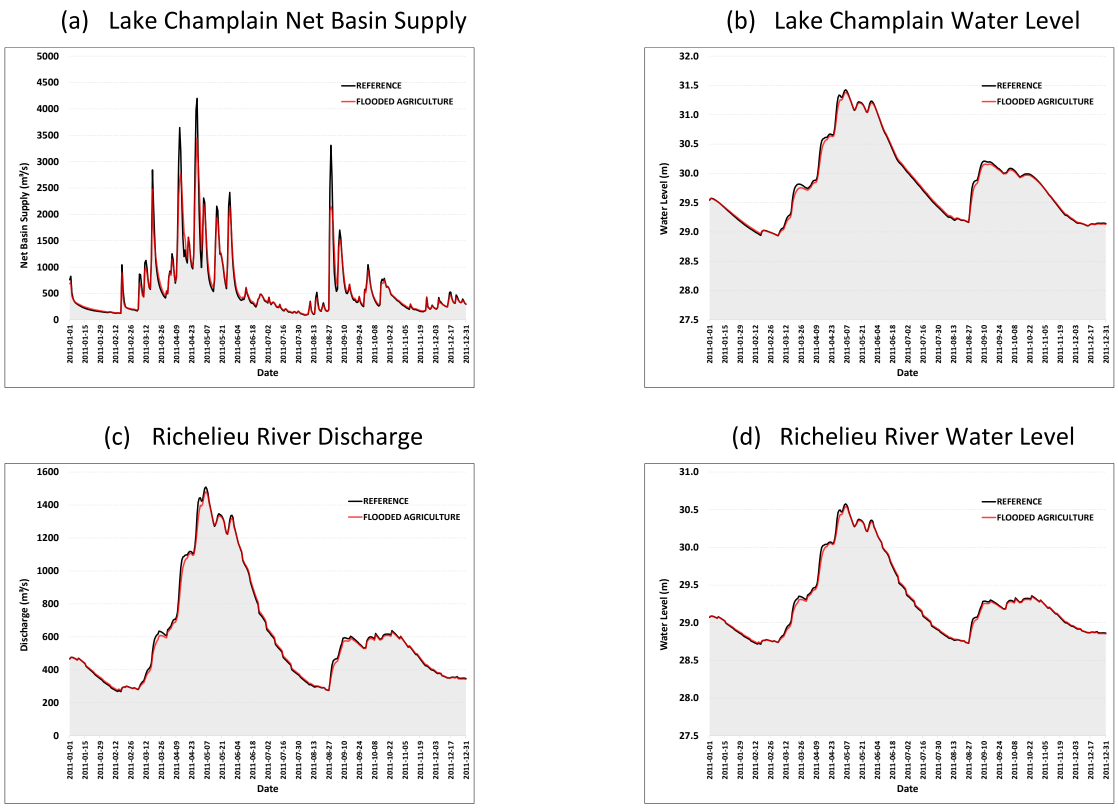


Figure 8.3 Impact of water storage on riparian agricultural landscapes of the LCRR basin on NBS flows (a) , LC water level (b), discharge in the RR at the Rapid Fryers (c) and RR water level (Saint-Jean Marina) (d) given the 2011 conditions using HYDROTEL and WBM at a daily time step.

Table 8.3 summarizes the effect of the agricultural land water storage scenario given the 2011 conditions.

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 Rapid Fryers and RR water levels (Saint-Jean Marina) given the 2011 conditions (Reference).

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%)

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. But the benefits are not in the same proportion for the Richelieu River discharges (-2.0%), but the water level reduction is consistent (- 4 cm). It remains important to remind that such scenario include considerable additional storage area and would be challenging to implement. Thus, on a daily time scale, large-scale storing of water on riparian agricultural landscapes could have provided significant relief in 2011.

9 Wetland construction/restoration scenarios

9.1 Wetland construction/restoration scenario based on spatial data

Based on readily available spatial data, we have designed a first-hand approach to build wetland construction/restoration scenarios. This approach is based on two specific spatial components: the digital elevation model (DEM) and the land cover map.

The approach can be described as follows:

1. Location of depressions (a.k.a. pits) in the DEM (letter B Figure 9.1).
2. Using the flow matrix, identification of the converging tiles towards the pit. Those tiles adjacent to the pit represent the level one (1) depression capacity.
3. Building the depression capacity level by level. Tile adjacent and converging to level one (1) tiles represent the level two (2), repeating this process allows for the delineation of all potential depression areas of the DEM.
4. Identification of various depressions with different design criteria (e.g., threshold level for storage capacity, wetland area; that is number of tiles converging towards the deepest tile (green tiles on Figure 9.1) and drainage/contributing area (blue tiles on Figure 7.1); that is minimum number tiles 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.

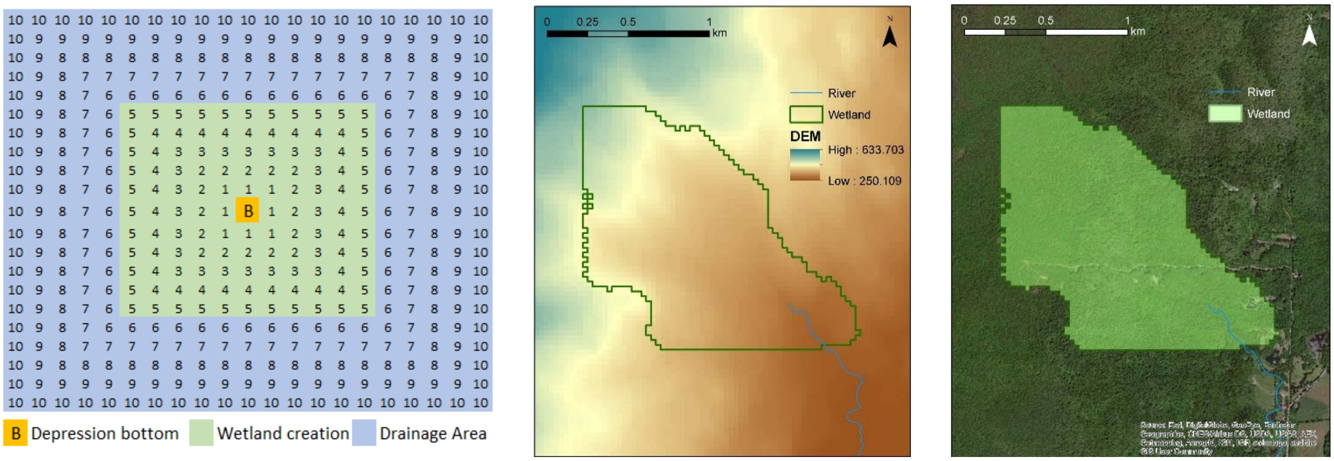


Figure 9.1 Development of a wetland scenario using a DEM and a few design criteria (e.g., wetland area or number of tiles converging towards the deepest tile and drainage area or minimum number tiles converging towards the wetland area).

Using this approach, we built a conservative wetland construction/restoration scenario and evaluated the associated added value. According to the estimation made in Chapter 7 to reduce the 2011 peak flow at Rapid Fryers by 5%, we developed a first scenario corresponding to the addition of 652 km² of wetlands regardless of the sub-watershed (649 km² in the Richelieu River watershed upstream of the Rapid Fryers point including 647 km² in the Lake Champlain watershed. Figure 9.2 illustrates a general representation of this scenario.

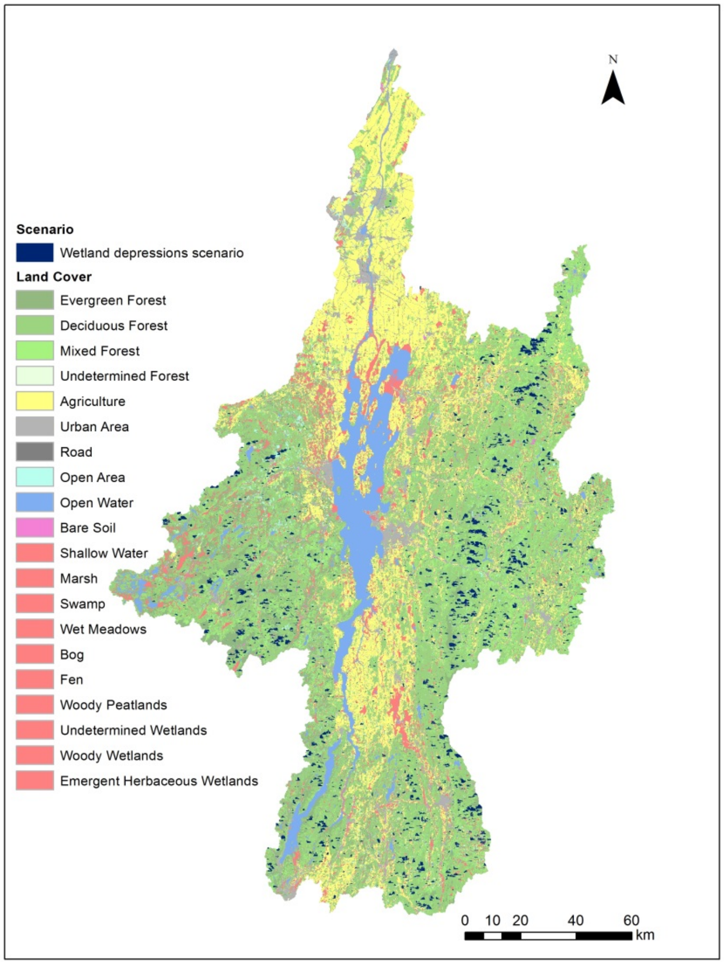


Figure 9.2 General representation of the wetland scenario using the DEM.

Table 9.1 describes for all sub-watersheds, the impact of adding 652 km² of wetlands on the LCRR wetland area and wetland drainage area. For this scenario we performed a hydrological simulation 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 6; that is the calculation procedure was as follows:

For high flows: $(Current\ Wetlands - Wetland\ \ Scenario)/Current\ Wetlands$ where a positive result corresponded to a high flow attenuation.

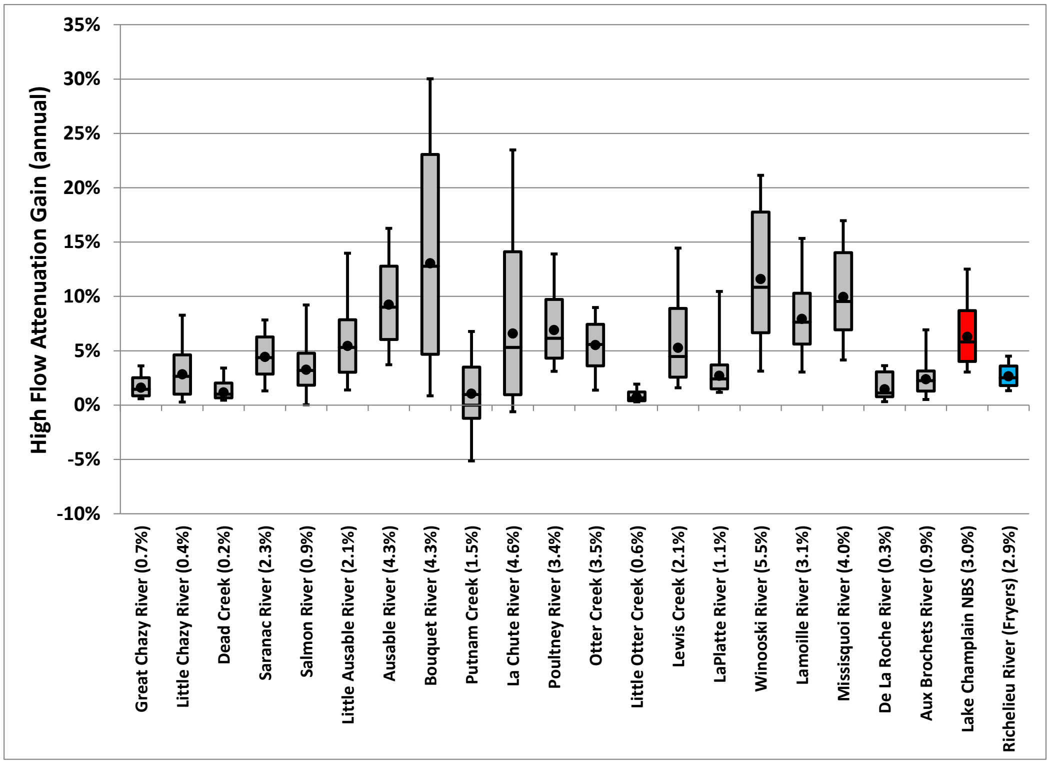
Meanwhile for low flows: $(Wetland\ Scenario - Current\ Wetlands)/Current\ Wetlands$ where a positive result corresponded to a low flow amplification.

Figure 9.2 highlights the impact (annual, spring, summer/autumn) of the wetland scenario on high flow attenuation. As this study puts the emphasis on high flow and flood risk, the impact of the wetland scenario on the gain in low flow amplification are reported in Appendix II (Figures A 8-10). Table 9.2 summarizes the annual impact of the wetland scenario on the gains in high flow attenuation for the 20 major LC sub-watersheds, LC NBS, RR flows at the Rapid Fryers and 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.

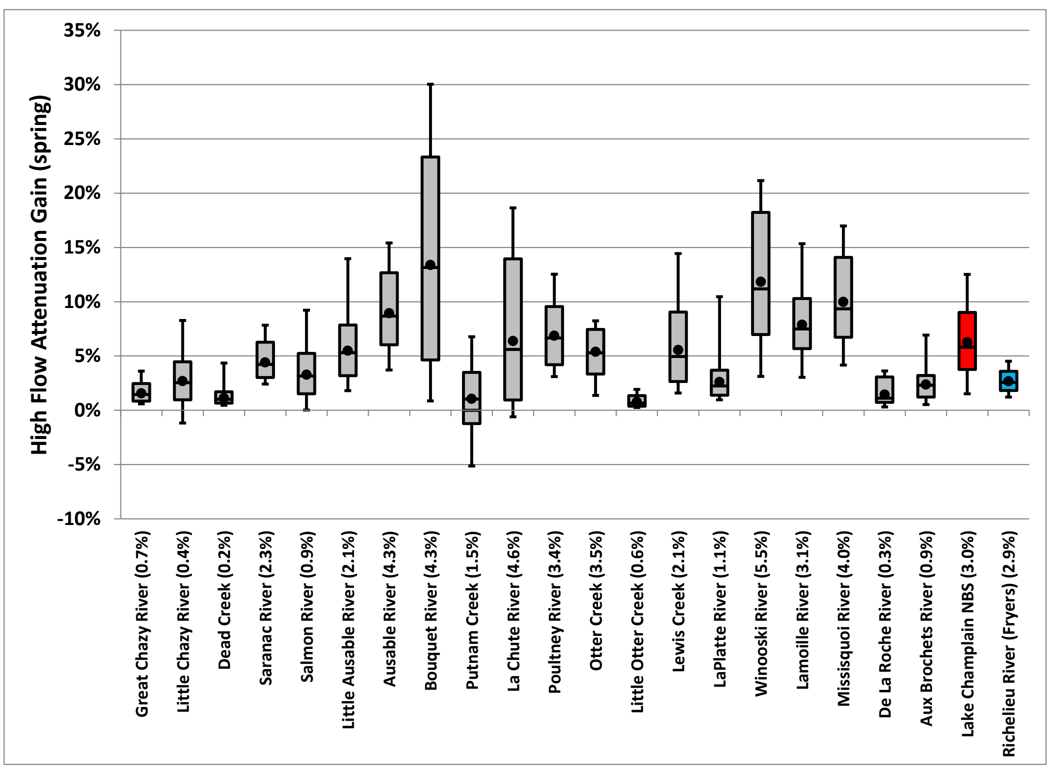
Table 9.1 Spatial impact of the wetland scenario on the LCRR basin for the 20 LC sub-watersheds, LC NBS and RR flows at Rapid Fryers.

#	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%**

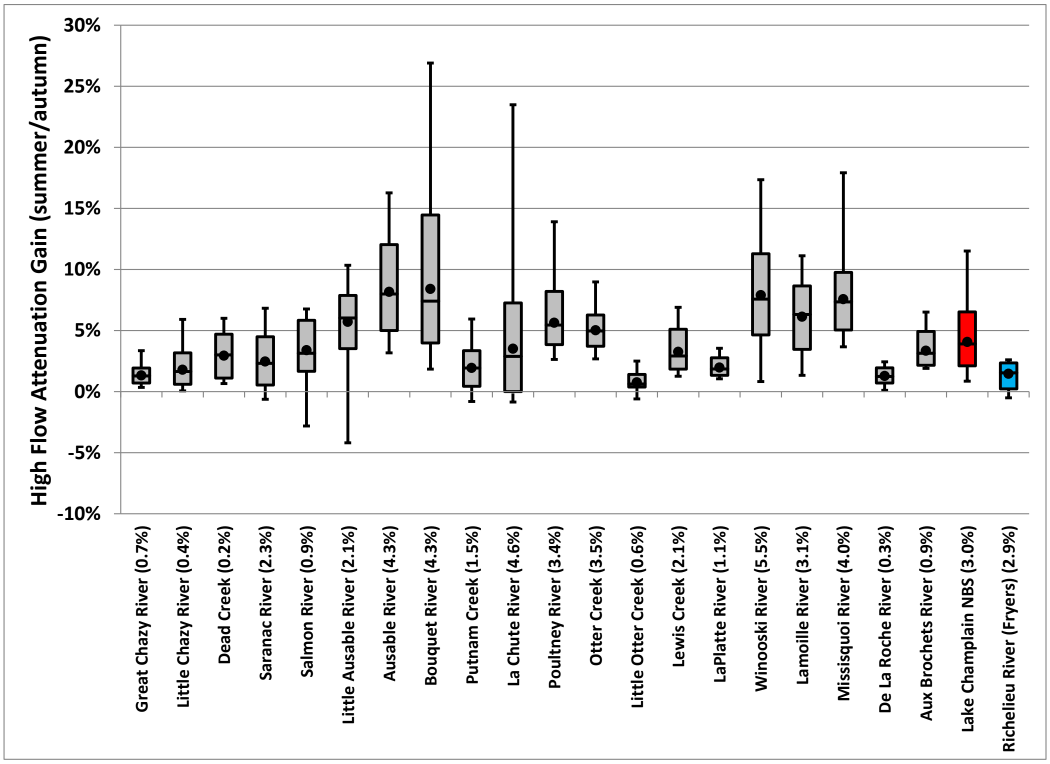
*The gains mean an increase in wetland area (for example Great Chazy with the addition of wetlands we have 27.2% (13.8% of wetland land cover + 0.7% of additional wetland) of the watershed in wetland area.


High Flow Attenuation Gain (annual)
35%
30%
25%
20%
15%
10%
5%
0%
-5%
-10%
Great Chazy River (0.7%)
Little Chazy River (0.4%)
Dead Creek (0.2%)
Saranac River (2.3%)
Salmon River (0.9%)
Little Ausable River (2.1%)
Ausable River (4.3%)
Bouquet River (4.3%)
Putnam Creek (1.5%)
La Chute River (4.6%)
Poultney River (3.4%)
Otter Creek (3.5%)
Little Otter Creek (0.6%)
Lewis Creek (2.1%)
LaPlatte River (1.1%)
Winooski River (5.5%)
Lamoille River (3.1%)
Missisquoi River (4.0%)
De La Roche River (0.3%)
Aux Brochets River (0.9%)
Lake Champlain NBS (3.0%)
Richelieu River (Fryers) (2.9%)

(a)


High Flow Attenuation Gain (spring)
35%
30%
25%
20%
15%
10%
5%
0%
-5%
-10%
Great Chazy River (0.7%)
Little Chazy River (0.4%)
Dead Creek (0.2%)
Saranac River (2.3%)
Salmon River (0.9%)
Little Ausable River (2.1%)
Ausable River (4.3%)
Bouquet River (4.3%)
Putnam Creek (1.5%)
La Chute River (4.6%)
Poultney River (3.4%)
Otter Creek (3.5%)
Little Otter Creek (0.6%)
Lewis Creek (2.1%)
LaPlatte River (1.1%)
Winooski River (5.5%)
Lamoille River (3.1%)
Missisquoi River (4.0%)
De La Roche River (0.3%)
Aux Brochets River (0.9%)
Lake Champlain NBS (3.0%)
Richelieu River (Fryers) (2.9%)

(b)



(c)

Figure 9.3 Gain in high flow attenuation gain when adding 652 km^2 of wetland in the LCRR basin for the 20 LC sub-watersheds, LC NBS and RR flows at Rapid Fryers compare to current conditions (Min; Max; 10th centile; 90th centile; Median; Average) for various temporal scales: (a) annual, (b) spring and (c) summer/fall.

Table 9.2 Gain in annual high flow attenuation when adding 652 km^2 of wetland in the LCRR basin for the 20 LC sub-watersheds, LC NBS, RR flows at Rapid Fryers and LC and RR (Saint-Jean Marina) compared to current conditions.

#	WATERSHED	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***

For sub-watersheds with a high percentage gain of additional wetlands, we observed a proportional effect on high flows when compared sub-watersheds with smaller increase in wetland area. Figure 9.2 the impacts vary from year to year each sub-watersheds. The annual and spring attenuation gains are similar since the highest flow occurs most of the time during spring. Figure 9.2 shows that for tree (3) sub-watersheds (Little Chazy River, Putman Creek and La Chute) annual or spring results include negative impacts (increase of high flows) and, for seven (7) sub-watershed (Saranac, Salmon, Little Ausable, Putman Creek La Chute and Richelieu River (Fryers)), autumn results include negative impacts. Such negative values suggest that for certain years, additional wetlands land could worsen the high flows. But is important to also mention that all median or average attenuation gain results are positive.

Table 9.2 displays variable maximum or minimum year impacts and contributions of additional wetlands for specific 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 Rapid Fryers 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 the LC and 3 cm at the St-Jean-sur-le-Richelieu marina). Thus, given the results obtained from this hydrological modeling exercise, using a daily time step, increasing the wetland area by 3% could prove to provide a valuable mitigation measure.

9.1.1 Effect of wetland construction/restoration scenario on the 2011 flood

In this section, we again focus on the 2011 hydrographs at various spatial scales, comparing simulation results related to the current effect of wetlands and those of this wetland 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.

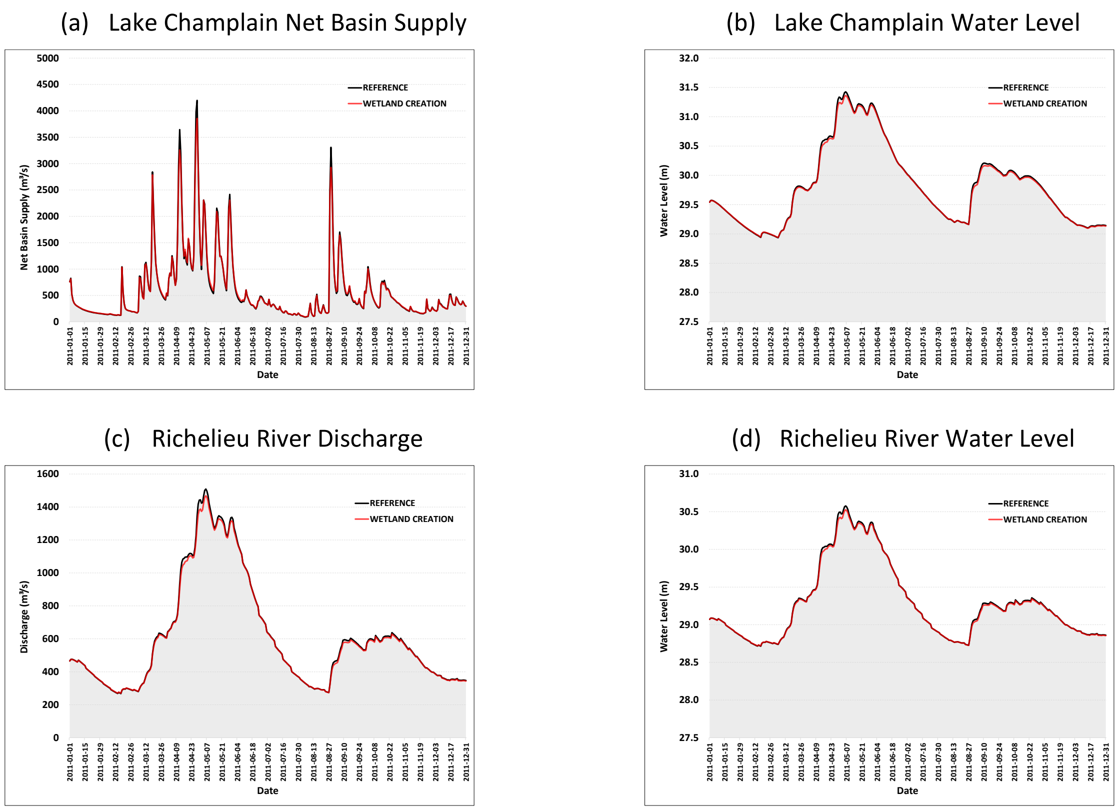


Figure 9.4 Impact of wetlands creation/restoration scenario in the LCRR basin on NBS flows (a), LC water level (b), and flows in the RR at the Rapid Fryers (c) and RR water level (Saint-Jean Marina) (d) given the 2011 conditions using HYDROTEL and WBM at a daily time step.

Table 9.3 summarizes the results of the wetland scenario given the 2011 conditions.

Table 9.3 Summary of the effects of the wetland scenario on NBS flows, LC water level, discharge in the RR at the Rapid Fryers and RR water level (Saint-Jean Marina) given the 2011 conditions (Reference).

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%)

Increased water storage area by adding additional wetlands to decreased Lake Champlain net basin supply peak flows inducing a decreased in the lake water level. Also damping impact of Lake Champlain limits the benefits on the Richelieu River discharges but water level but water level reduction are consistent. Thus such scenario of wetlands creation could also be a beneficial practice relevant at the scale of Lake Champlain contributing sub-watershed with flooding problematics.

9.2 USEPA wetland scenario

The EnviroAtlas Potential Wetland Areas (PWA) dataset of the United States Environmental Protection Agency (USEPA) shows for Vermont and New York State the potential locations of additional wetland areas at a 30-meter resolution. 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. Potential wetlands were identified as areas naturally accumulating water due to topography and 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. This source of information (https://www.epa.gov/enviroatlas) 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 (https://edg.epa.gov/data/Public/ORD/EnviroAtlas) or as an EnviroAtlas map service. Additional descriptive information about each attribute in this dataset can be found in its associated EnviroAtlas Fact Sheet (https://www.epa.gov/enviroatlas/enviroatlas-fact-sheets). Using the wetland areas with the highest development potential, we overlaid the geographical locations on the current land cover map to build a USEPA wetland scenario; including the addition of 865 km^2 of wetlands in the Lake Champlain basin.

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

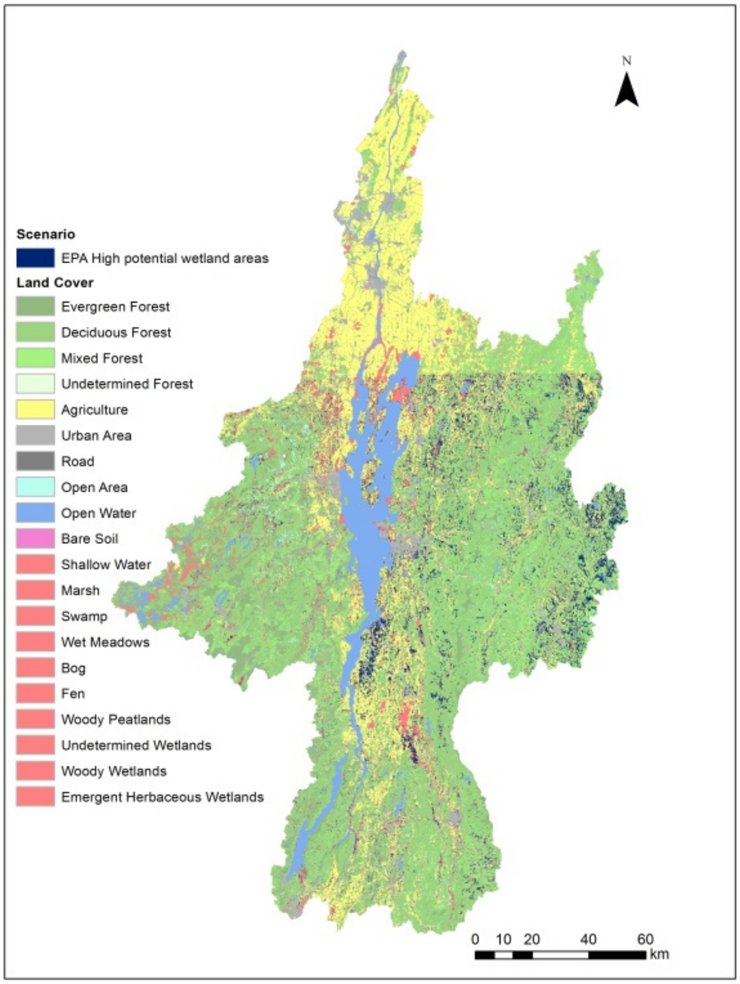


Figure 9.5 General representation of the USEPA high potential wetland area scenario.

Table 9.4 describes for each sub-watershed, the impact of the USEPA high potential wetland scenario on the LCRR wetland area and wetland drainage area. For this scenario we performed a hydrological simulation 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 Chapters 6, 7 and 8; that is the calculation procedure was as follows:

For high flows: $(Current\ Wetlands - Wetland\ \ Scenario)/Current\ Wetlands$ were a positive result corresponds to a high flow attenuation.

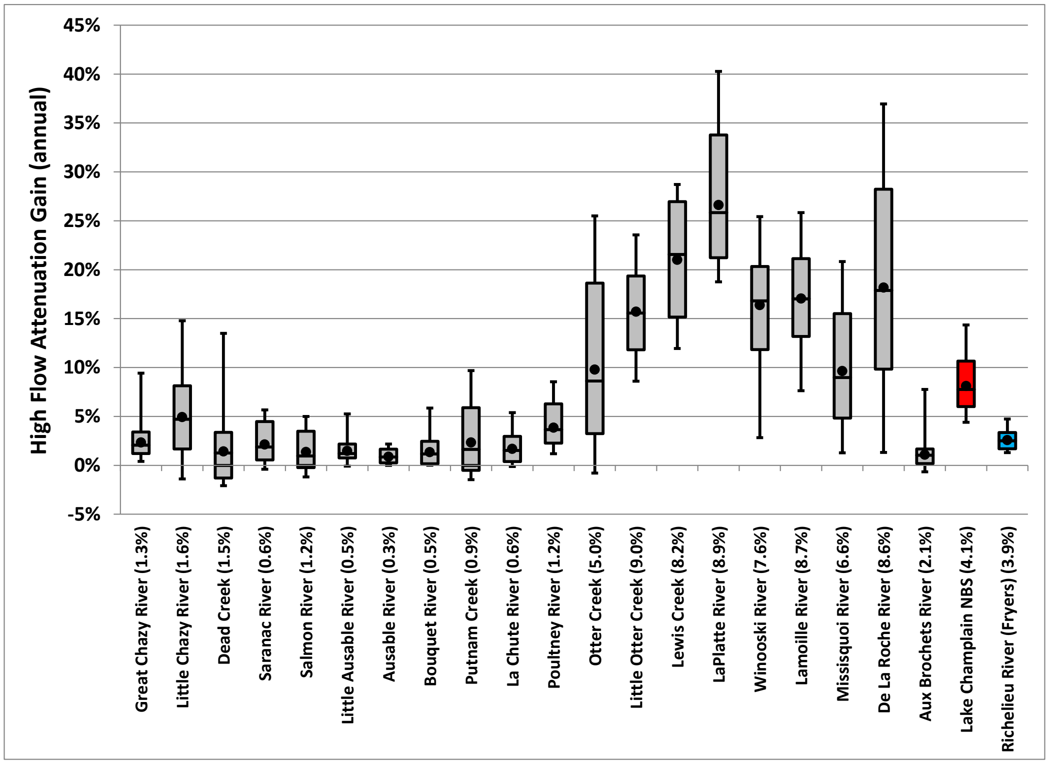
For low flows: $(Wetland\ Scenario - Current\ Wetlands)/Current\ Wetlands$ were a positive result corresponds to a low flow amplification.

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 impact of the USEPA high potential wetland scenario on low flow amplification gain are reported in Appendix II (Figures A 11-13). Table 9.4 summarizes the annual impact of the USEPA scenario on the gains in high flow attenuation for the 20 major LC sub-watersheds, LC NBS, RR flows at the Rapid Fryers and 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.

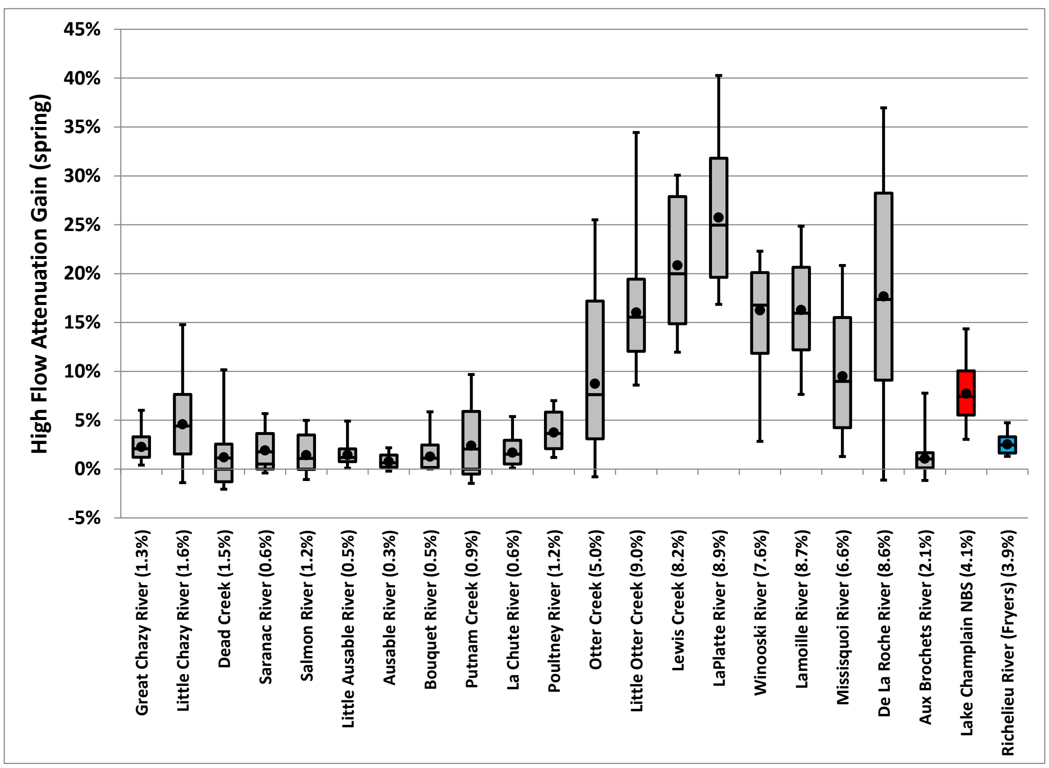
Table 9.4 Spatial impact of the EPA high potential wetlands scenario on the LCRR basin for the 20 LC sub-watersheds, LC NBS and RR flows at Rapid Fryers.

#	WATERSHED	DRAINAGE (km²)	Wetlands		vs. Watershed		W Drainage		vs. Watershed	
			(km²)	GAIN (km²)	(%)	GAIN (%)	(km²)	GAIN (km²)	(%)	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%**

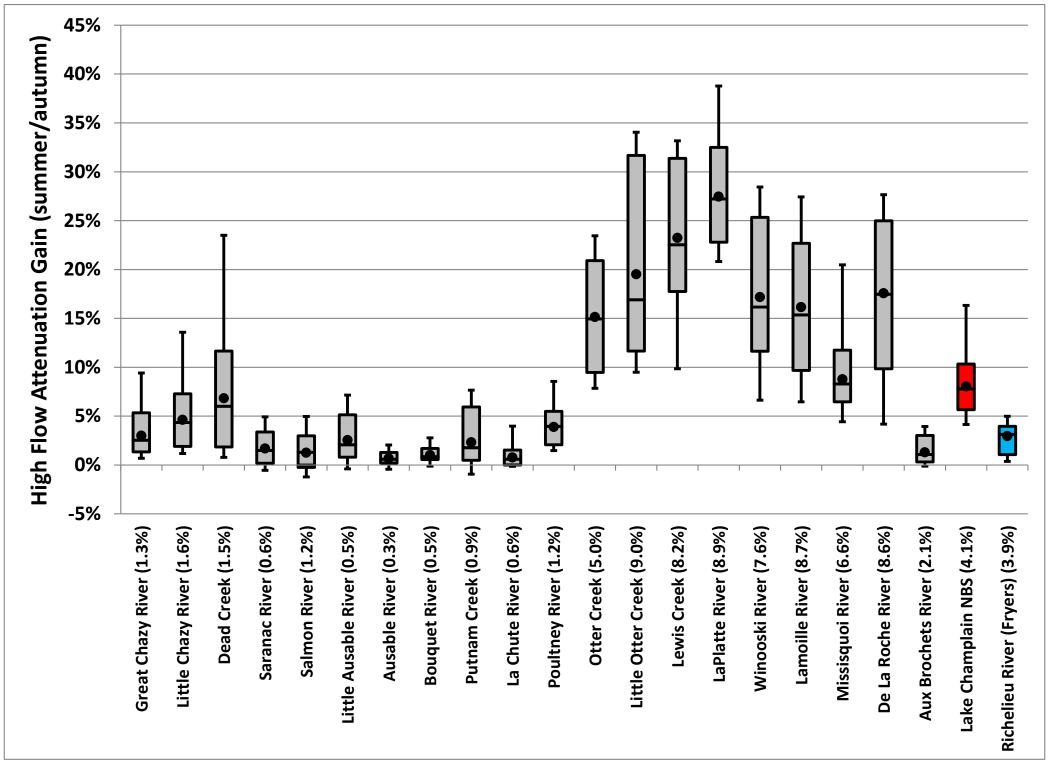
*The gains mean an increase in wetland area (for example Great Chazy with the addition of wetlands we have 15.1% (13.8% of wetland land cover + 1.3% of additional wetlands) of the watershed in wetland area.


High Flow Attenuation Gain (annual)
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
-5%
Great Chazy River (1.3%)
Little Chazy River (1.6%)
Dead Creek (1.5%)
Saranac River (0.6%)
Salmon River (1.2%)
Little Ausable River (0.5%)
Ausable River (0.3%)
Bouquet River (0.5%)
Putnam Creek (0.9%)
La Chute River (0.6%)
Poultney River (1.2%)
Otter Creek (5.0%)
Little Otter Creek (9.0%)
Lewis Creek (8.2%)
LaPlatte River (8.9%)
Winooski River (7.6%)
Lamoille River (8.7%)
Missisquoi River (6.6%)
De La Roche River (8.6%)
Aux Brochets River (2.1%)
Lake Champlain NBS (4.1%)
Richelieu River (Fryers) (3.9%)

(a)


High Flow Attenuation Gain (spring)
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
-5%
Great Chazy River (1.3%)
Little Chazy River (1.6%)
Dead Creek (1.5%)
Saranac River (0.6%)
Salmon River (1.2%)
Little Ausable River (0.5%)
Ausable River (0.3%)
Bouquet River (0.5%)
Putnam Creek (0.9%)
La Chute River (0.6%)
Poultney River (1.2%)
Otter Creek (5.0%)
Little Otter Creek (9.0%)
Lewis Creek (8.2%)
LaPlatte River (8.9%)
Winooski River (7.6%)
Lamoille River (8.7%)
Missisquoi River (6.6%)
De La Roche River (8.6%)
Aux Brochets River (2.1%)
Lake Champlain NBS (4.1%)
Richelieu River (Fryers) (3.9%)

(b)



(c)

Figure 9.6 High flows attenuation gain of the EPA high potential wetlands scenario on the LCRR basin for the 20 LC sub-watersheds, LC NBS and RR flows at Rapid Fryers compare to current conditions (┴ Min; ┬ Max; 10th centile; 90th centile; Median; Average) for various temporal scales: (a) annual, (b) spring and (c) summer/fall.

Table 9.5 Gains in annual high flow attenuation of the USEPA high potential wetland scenario on the LCRR basin for the 20 LC sub-watersheds, LC NBS, RR flows at Rapid Fryers and LC and RR (Saint-Jean Marina) compared to current conditions.

#	WATERSHED	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***

For this USEPA scenario, sub-watersheds with a high percentage gain of additional wetlands (mostly located in Vermont), we observed a significantly higher impact on high flows when compared to sub-watersheds with smaller percentage gains. Figure 9.6 illustrates the impacts vary from year to year each sub-watersheds. 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 nine (9) sub-watersheds (Little Chazy, Dead Creek, Saranac, Salmon, Ausable. Putman 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) sub-watersheds (Saranac, Salmon, Little Ausable, Putman Creek La Chute and Aux Brochets) autumn results include negative impacts. Such negative values suggest that for certain years, additional wetlands land could worsen the high flows, but it is noteworthy that all median or average attenuation gains are positive.

Table 9.5 indicates variable maximum or minimum year impacts and contribution of additional wetlands for specific 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 allows to decrease the highest daily NBS peak flows by 8.1% on average and the peak flow at Rapid Fryers on the Richelieu River (RR) by 2.6% on average when compared to the current conditions. Such reductions are also felt on water levels of Lake Champlain and Richelieu River. These results demonstrate that the USEPA scenario could provide an effective flood mitigation specifically for the state of Vermont.

9.2.1 Effect of USEPA wetland scenario on the 2011 flood

In this section, we focus on 2011 hydrographs 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.

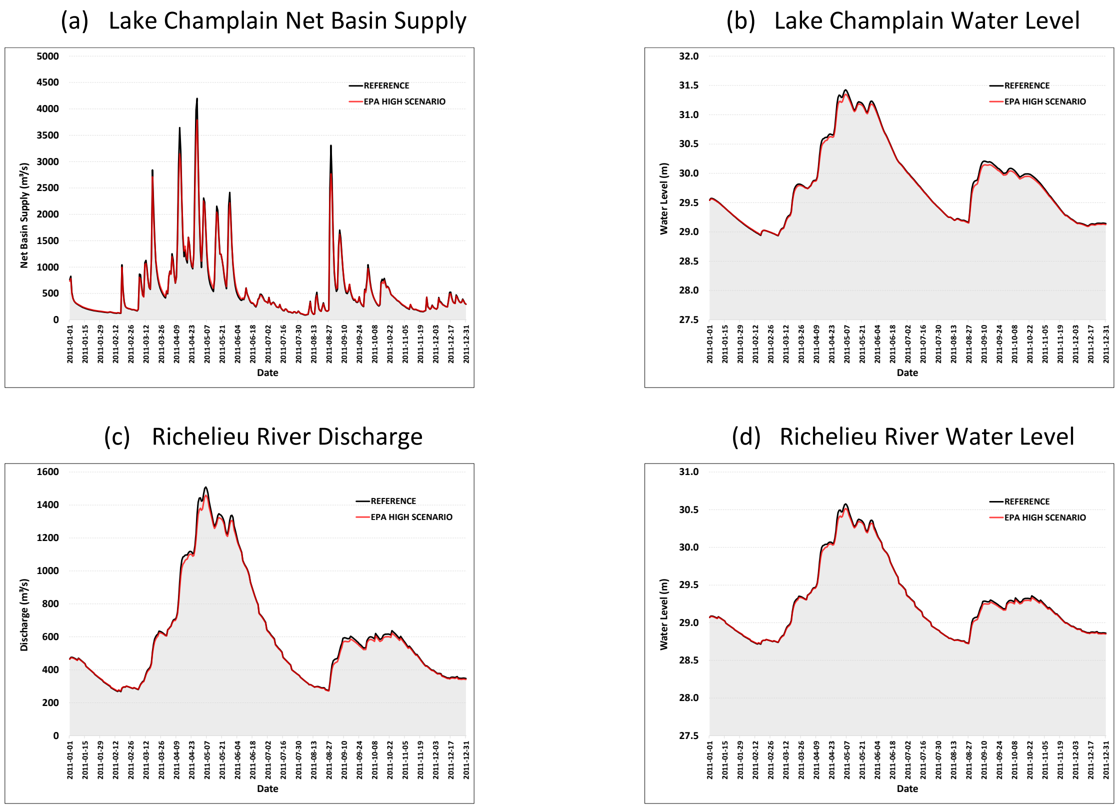


Figure 9.7 Impact of the USEPA high potential wetland scenario in the LCRR basin on NBS flows (a), LC water level (b), discharge in the RR at the Rapid Fryers (c) and RR water level (Saint-Jean Marina) (d) given the 2011 conditions using HYDROTEL and WBM at a daily time step.

Table 9.6 summarizes the USEPA scenario considering the 2011 conditions.

Table 9.6 Summary of EPA wetlands scenario impact on NBS flows, LC water level, discharge in the RR at the Rapid Fryers and RR water level (Saint-Jean Marina) given the 2011 conditions (Reference).

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%)

Based on the USEPA scenario, an increase of water storage by adding wetlands could contribute to decreased Lake Champlain NBS peak flows by 9.7% leading to reducing the lake water level by 8 cm. Meanwhile, 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 certainly relevant for Lake Champlain and has the potential to provide beneficial effects at the local scale of various river segments in located in the state of Vermont.

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 1493 km² of wetlands in the Lake Champlain basin (see Figure 9.8)

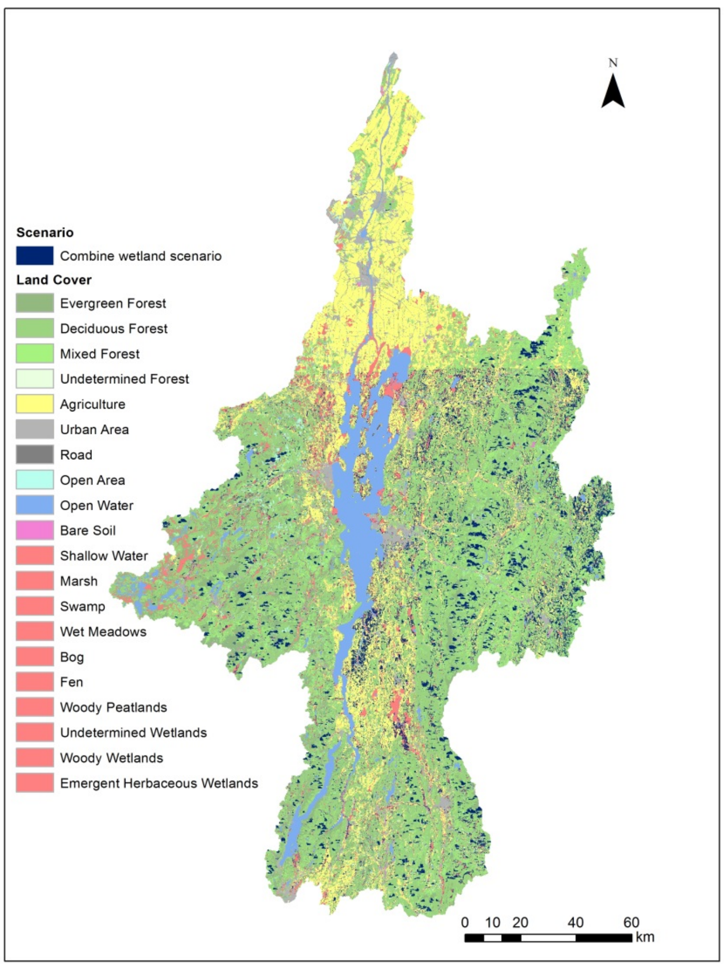


Figure 9.8 General representation of the combined wetland scenarios.

Table 9.7 presents, for every sub-watersheds, the resulting distribution of wetland area and wetland drainage area. The same approach was used to assess the outcome of the combined scenarios. And thus the calculation procedure remains:

For high flows: $(Current\ Wetlands - Wetland\ \ Scenario)/Current\ Wetlands$ where a positive result corresponds to a high flow attenuation.

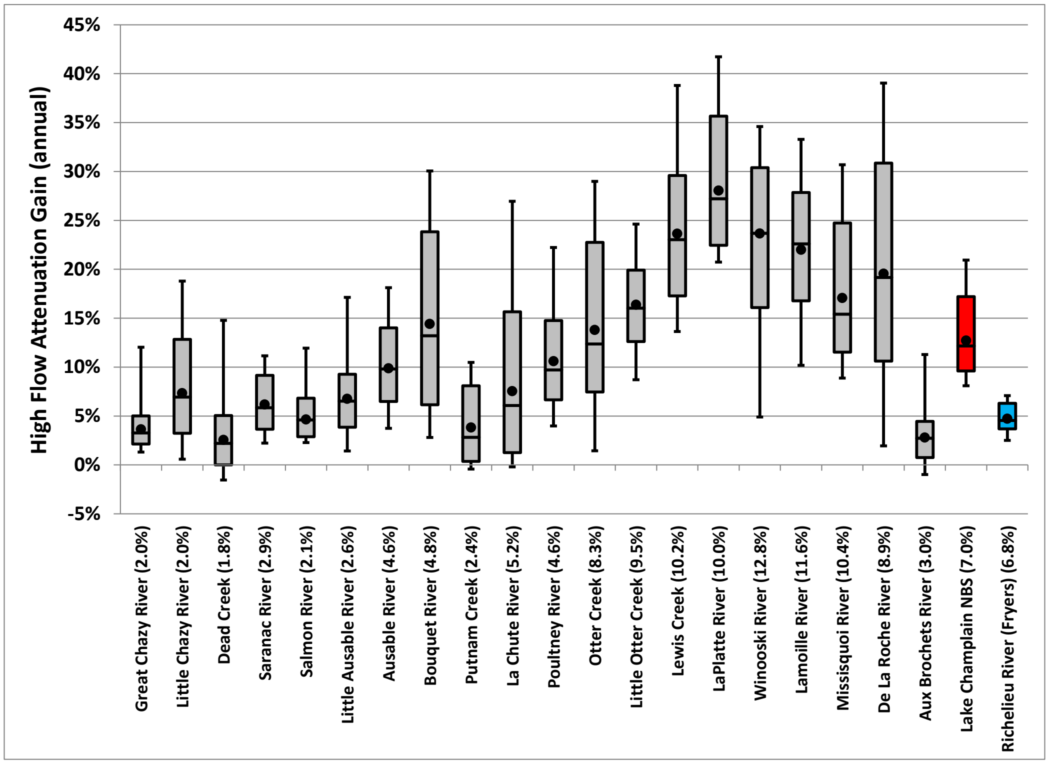
For low flows: $(Wetland\ Scenario - Current\ Wetlands)/Current\ Wetlands$ where a positive result corresponds to a low flow amplification.

Figure 9.9 highlights the impact (annual, spring, summer/autumn) of the combined scenarios on high flows attenuation. Similarly, low flow amplification gains are reported in Appendix II (Figures A 14-16). Table 9.8 summarizes the annual effect on high flow attenuation for the 20 major LC sub-watersheds, LC NBS, RR flows at the Rapid Fryers and water levels of the LC and RR (Marina Saint-Jean); and results for specific flood years are also introduced.

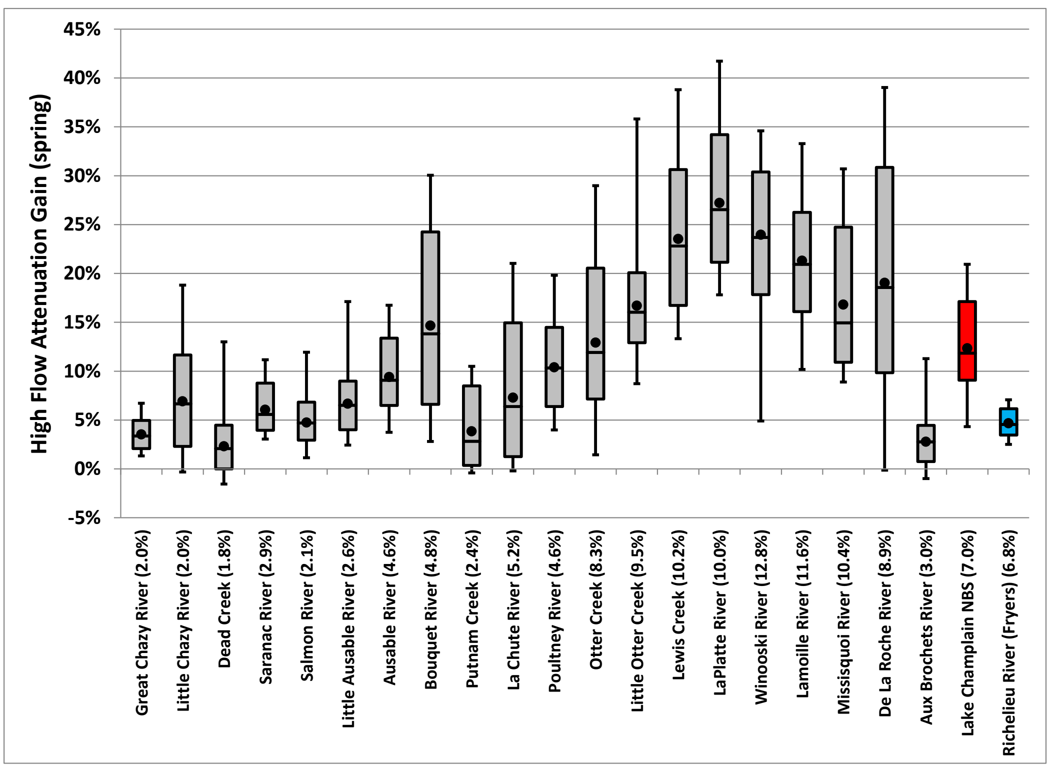
Table 9.7 Spatial impact of the combined wetland scenarios on the LCRR basin for the 20 LC sub-watersheds, LC NBS and RR flows at Rapid Fryers.

#	WATERSHED	DRAINAGE (km²)	Wetlands		vs. Watershed		W Drainage		vs. Watershed	
			(km²)	GAIN (km²)*	(%)	GAIN (%)*	(km²)	GAIN (km²)	(%)	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%

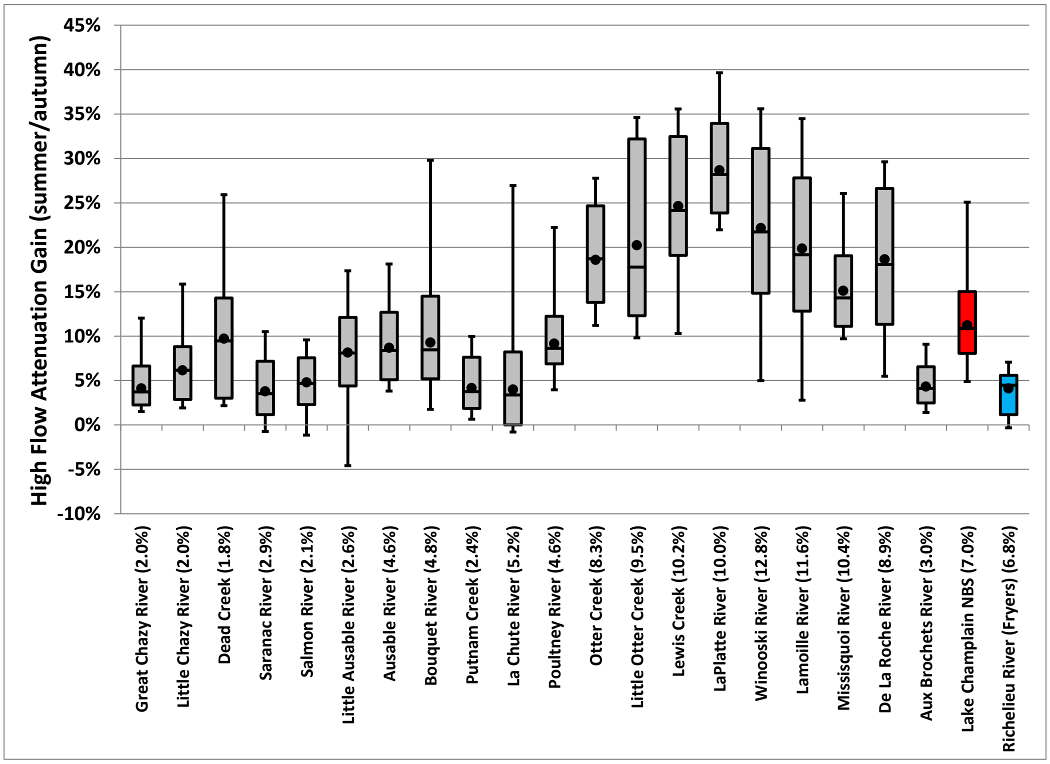
*The gains mean an increase in wetland area (for example Great Chazy with the addition of wetlands we have 15.7% (13.8% of wetland land cover + 2.0% of additional wetlands) of the watershed in wetland area.


High Flow Attenuation Gain (annual)
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
-5%
Great Chazy River (2.0%)
Little Chazy River (2.0%)
Dead Creek (1.8%)
Saranac River (2.9%)
Salmon River (2.1%)
Little Ausable River (2.6%)
Ausable River (4.6%)
Bouquet River (4.8%)
Putnam Creek (2.4%)
La Chute River (5.2%)
Poultney River (4.6%)
Otter Creek (8.3%)
Little Otter Creek (9.5%)
Lewis Creek (10.2%)
LaPlatte River (10.0%)
Winooski River (12.8%)
Lamoille River (11.6%)
Missisquoi River (10.4%)
De La Roche River (8.9%)
Aux Brochets River (3.0%)
Lake Champlain NBS (7.0%)
Richelieu River (Fryers) (6.8%)

(a)


High Flow Attenuation Gain (spring)
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
-5%
Great Chazy River (2.0%)
Little Chazy River (2.0%)
Dead Creek (1.8%)
Saranac River (2.9%)
Salmon River (2.1%)
Little Ausable River (2.6%)
Ausable River (4.6%)
Bouquet River (4.8%)
Putnam Creek (2.4%)
La Chute River (5.2%)
Poultney River (4.6%)
Otter Creek (8.3%)
Little Otter Creek (9.5%)
Lewis Creek (10.2%)
LaPlatte River (10.0%)
Winooski River (12.8%)
Lamoille River (11.6%)
Missisquoi River (10.4%)
De La Roche River (8.9%)
Aux Brochets River (3.0%)
Lake Champlain NBS (7.0%)
Richelieu River (Fryers) (6.8%)

(b)



(c)

Figure 9.9 Gains in high flows attenuation of the combined wetland scenarios on the LCRR basin for the 20 LC sub-watersheds, LC NBS and RR flows at Rapid Fryers compare to current conditions (Min; Max; 10th centile; 90th centile; Median; Average): for various temporal scales: (a) annual, (b) spring and (c) summer/fall.

Table 9.8 Gains in annual high flow attenuation of the combined wetland scenariod on the LCRR basin for the 20 LC sub-watersheds, LC NBS, RR flows at Rapid Fryers and LC and RR (Saint-Jean Marina) compared to current conditions.

#	WATERSHED	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***

For sub-watersheds with a high percentage gain of additional wetland area, we observe a significantly higher impact on high flows when compared sub-watersheds with smaller percentage gain; that is more so for Vermont's sub-watersheds. Figure 9.9 illustrates the impacts vary from year to year each sub-watersheds. 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) sub-watersheds (Dead Creek, Putman Creek, La Chute and Aux Brochets), the annual or spring results include negative impacts (increase of high flows) and, meanwhile, for four (4) sub-watersheds (Saranac, Salmon, Little Ausable, and La Chute) autumn results also include negative impacts. Such negative values suggest that for certain years, additional wetlands land could worsen the high flows; but it is important also to mention that all median or average attenuation gains are positive.

Table 9.8 shows variable maximum or minimum year impacts and contribution of additional wetlands for specific 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 relief; reducing 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 at the daily time step the highest NBS peak flows by 12.7% on average; and the peak flow at the Rapid Fryers 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). On a daily time step evaluation pure hydrological approach, additional wetlands based on combine wetlands scenario at a large scale could better contribute to flood attenuation practice and be an effective flood mitigation water storage passive practice.

9.3.1 Effect of the combined wetland scenarios on the 2011 flood

In this section, we again focus on the 2011 hydrographs, comparing the effect of the current wetland distribution with those of the combined wetland scenarios using the aforementioned methodological approach; that is use of daily NBSs simulated by HYDROTEL as input to the daily LC WBM.

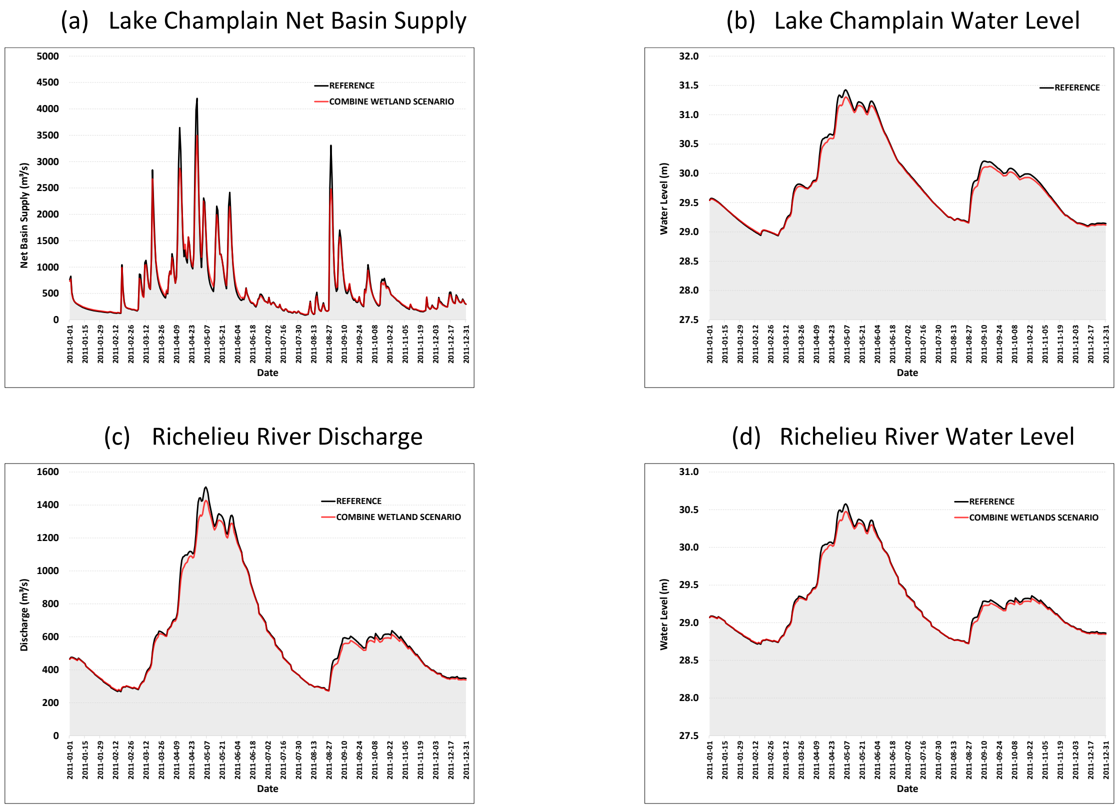


Figure 9.10 Effects of the combined wetland scenarios on the LCRR basin NBS flows (a), LC water levels (b), discharges in the RR at the Rapid Fryers (c) and RR water levels (Saint-Jean Marina) (d) given the 2011 conditions using HYDROTEL and WBM at a daily time step.

Table 9.9 Summary of the effects of the combines wetland scenarios on NBS flows, LC water levels, discharges in the RR at the Rapid Fryers and RR water levels (Saint-Jean Marina) given the 2011 conditions (Reference).

Wetlands	Lake Champlain Basin	Richelieu River (Fryer)
Area (km²)	21 254	22 055
Wetlands Area (km²)	3 039 (1 551)	3 106 (1 616)
Wetlands Drainage Area (km²)	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%)

Combining the wetland scenarios introduced in this Chapter would have decreased Lake Champlain NBS peak flows by 16.7% and induced lower lake water levels by 12 cm. However, the benefits on the Richelieu River discharges would have been the same, but the reduction in water levels would have been consistent (10 cm). It remains important to remind that such scenario include considerable additional storage area and would be challenging to implement. Thus, on a daily time scale, large-scale storing of water in wetlands could have provided significant relief in 2011.

10 Water storage mapping tool

Building manually an elaborate and specific scenario that is meant to represent water storage on agricultural or other landscapes can be a massive task can require tremendous amount of time that is 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. Thus, we built a specific GIS tool 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 use to achieve specify objectives or targets under diverse conditions or limitation using a graphical user interface (GUI) (see Figure 10.1). For now the GUI is in French.

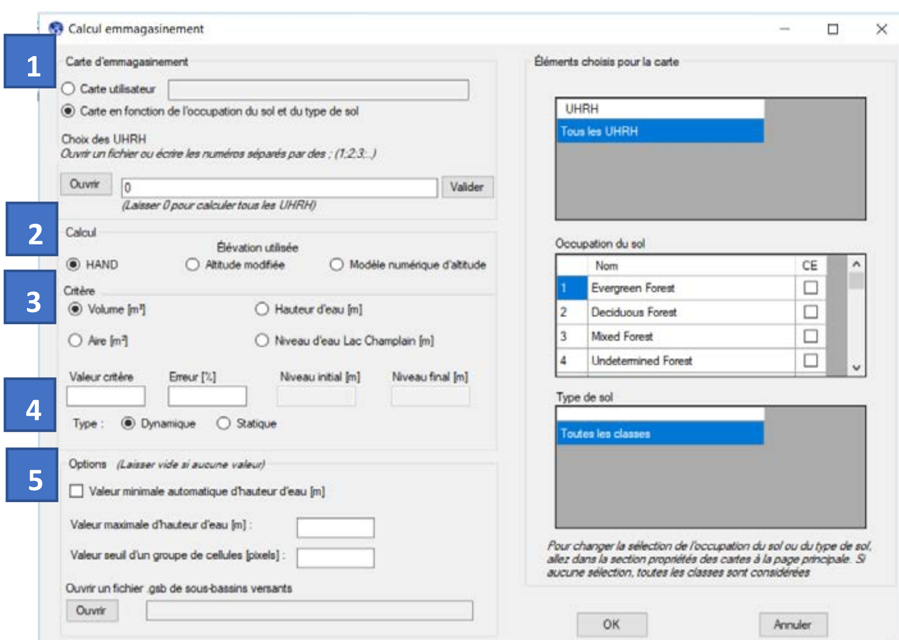


Figure 10.1 Water storage tool graphical user interface.

10.1.1 Mapping potential water storage

The potential water storage map (Tag 1, Figure 10.1) is used to delineate locations where it is desire to allow storage. There are two options, either a user-supplied map or building a potential map depending 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 the user must 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.

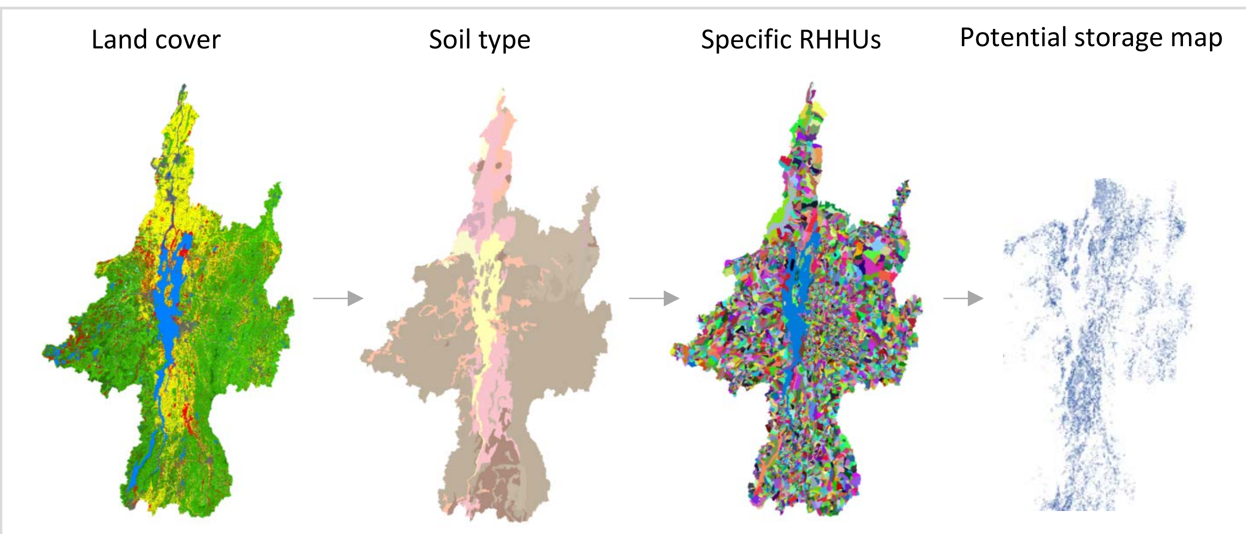


Figure 10.2 Basic steps to build a potential water storage map

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.

The “Height Above the Nearest Drainage” map, 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 et al., 2011). 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 a accumulation site where water would accumulate naturally and thus corresponds to samll 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.

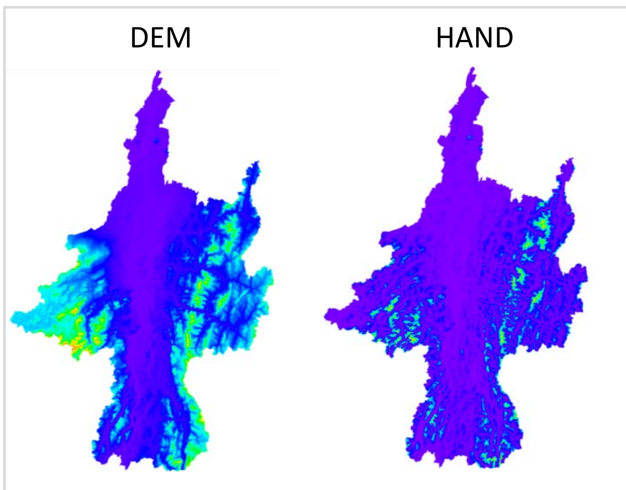


Figure 10.3 Reference elevation map

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 displpayed in Figure 10.4.

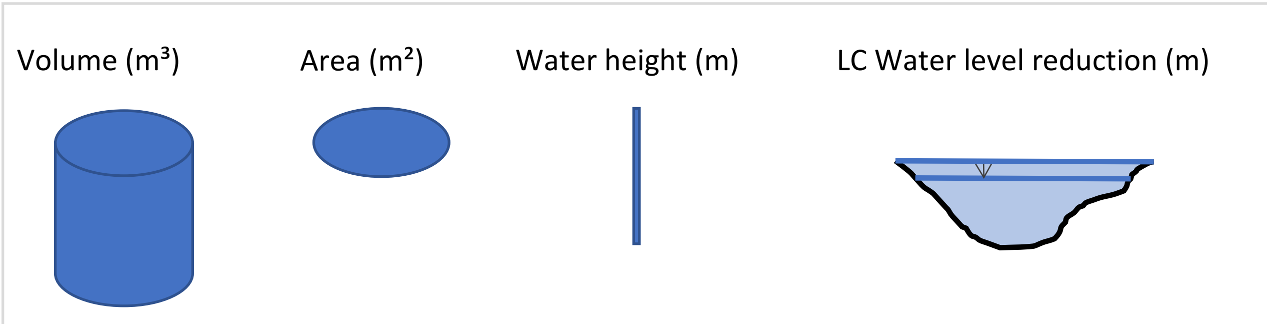


Figure 10.4 Calculation criteria

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 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.

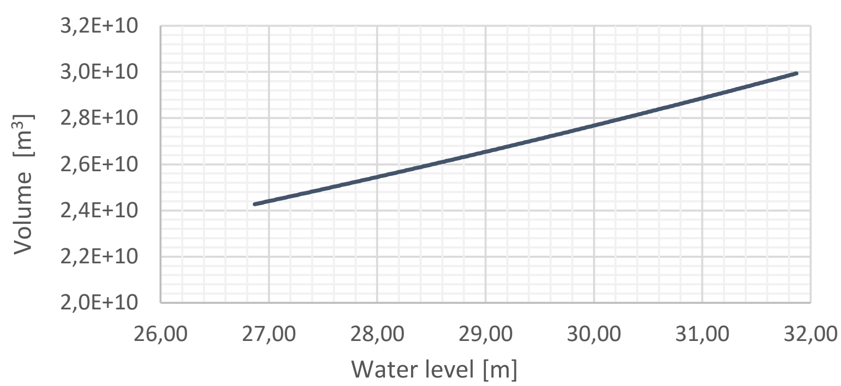


Figure 10.5 Relationship between the water level of Lake Champlain and the volume.

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.

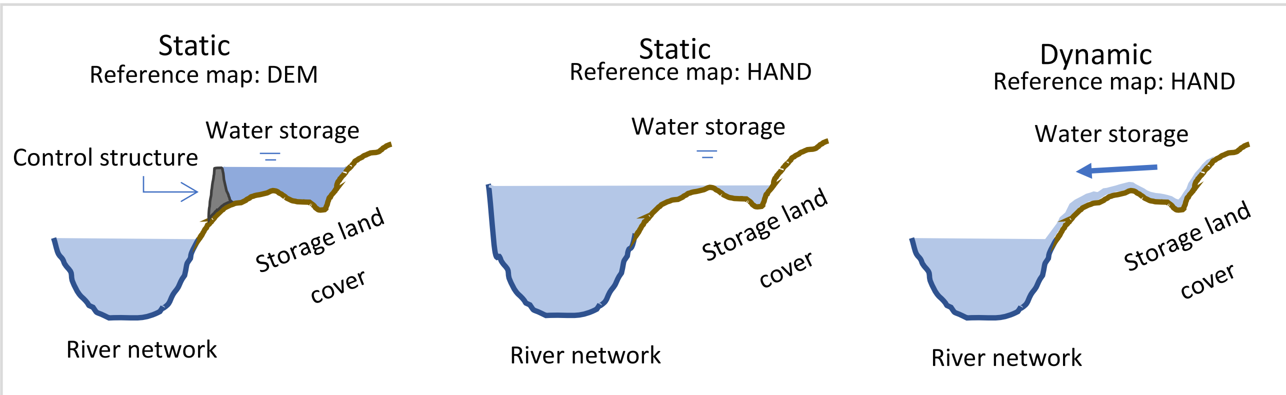


Figure 10.6 Water accumulation in the storage area

One of the advantage 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 one another and their respective minimum elevation value is considered when running the algorithm. This makes it possible to divide the territory into different sub-watersheds. 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.

10.1.5 Water storage options

Different options can be added to the input parameters allowing the user to specify certain characteristics or limitations. 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 therefore be reached while satisfying the maximum value. Otherwise, it could happened that the maximum water height would not 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 p. 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. In other words, to apply a filter on the storage map.

10.2 Analysis of the Lake Champlain and Richelieu River (LCRR) basin

This section analyzes the storage capacity of storing water on 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 Rapid Fryers hydrometric station and the black curve represents year 2011. The black horizontal line represents the threshold flow above which there is flooding.

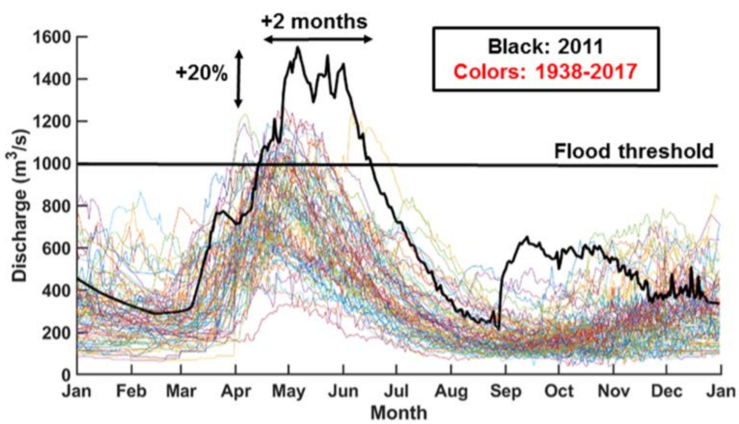


Figure 10.7 Daily flows of the RR at the Rapid Fryers hydrometric station for the 1938–2017 period. Each year is represented by a different color while 2011 is in black (Lucas-Picher et al,. 2019).

Integrating the area under the curve above the threshold value corresponds to approximately 1.612 x 10^9 m^3 of water. Similarly, we can determine approximately the flood volumes for all years. For this period a volume of 7.205 x 10^8 m^3 is found, which is approximately 2.23 times less than the 2011 volume. The difference between these two volumes is equivalent to 8.915 x 10^8 m^3. Therefore, it becomes interesting to apply for the LCRR basin the storage mapping tool. For this exercise water storage is strictly allowed on agricultural land for all soil types. In addition, to obtain a decrease in the water level of Lake Champlain, only RHHUs flowing into the lake are pre-selected. Finally, to filter the map, a threshold of 1000 pixels is applied on the storage map and an error of 0.5% is set for the calculation.

Four different analyses are performed according to different inputs. These analyses are introduced in Table 10.1.

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*

The storage maps resulting from the 4 tests are illustrated in Figure 10.8. The last two have are zoom in to see the details of the cells.

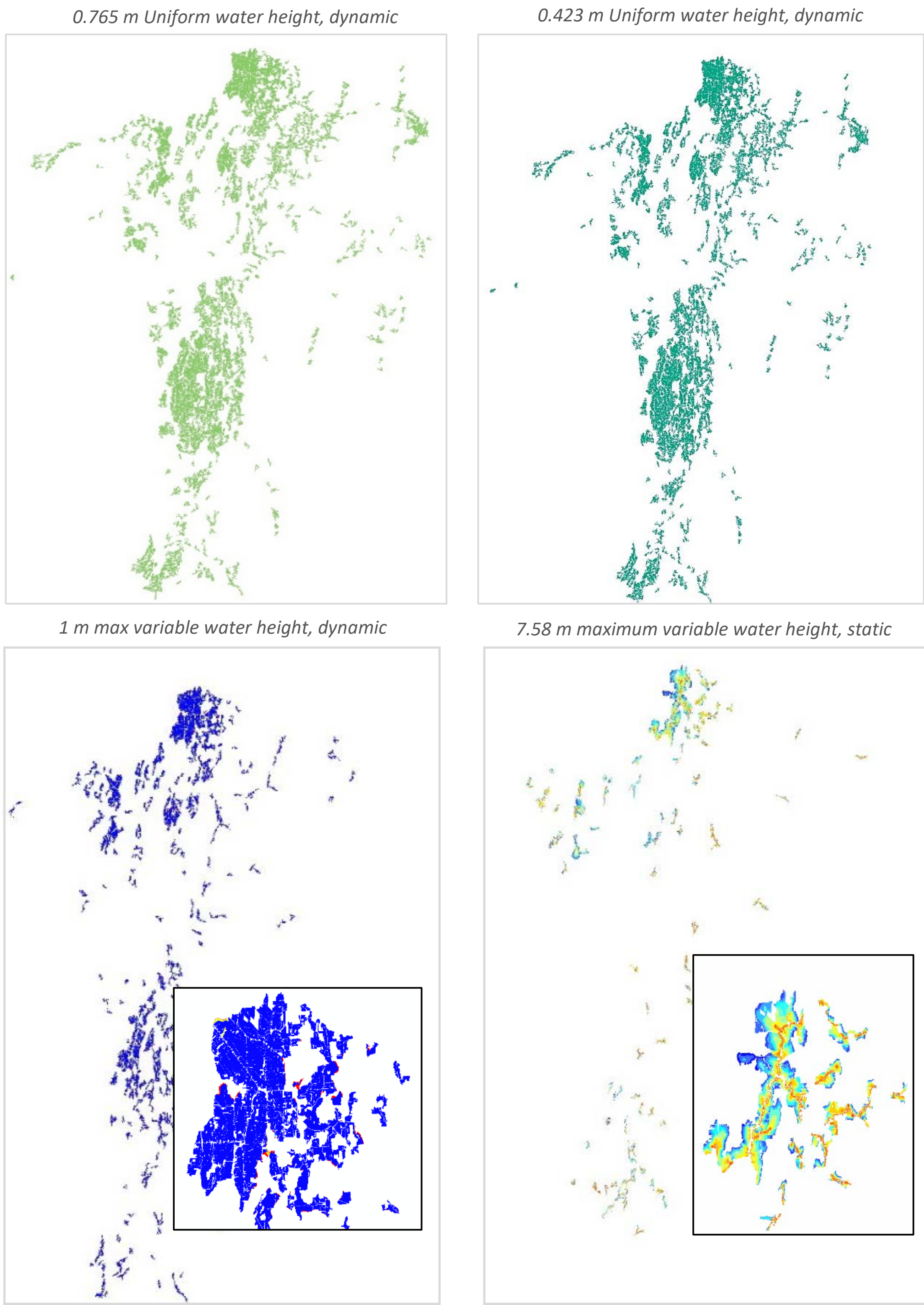


Figure 10.8 Resulting water storage map

For the first analysis, the minimum water height elevation allowed to store the target volume of 1.612 x 10^9 m^3 corresponds to 0.765 m. This water depth is 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 2108 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 is 0.423 m. This value is distributed evenly over the initial potential storage map. The area of 2108 km^2 remains unchanged. With the chosen options, reducing the volume to be stored by 45%, the water depth of the cells also decreases 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 requires a maximum water depth of 1 m for a dynamic storage. The final volume corresponds to 8.888 x 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, a zoom in is made on the storage map. Colors other than blue represent depths less than 1 m.

Finally, in the fourth analysis, the static type raises the water to fill in the depressions in the elevation map. This results in a map with values concentrated at the periphery of rivers and lakes which are the areas with the lowest elevations. The red color represents the highest water depth values. This map allows for the storage of a final volume of 8.918 x 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 ms, 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. Also when limiting to small water height, the required areas for storing the 2011 volume are very large, but smaller storage areas would require on the other end 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 area to support local queries or define where flood mitigation efforts should be concentrated.

11 Lessons learned, realisms, legacy and key messages

Based on this study some key elements can be highlighted. The PHYSITEL/HYDROTEL hydrologic modelling platform certainly provided a valuable framework to assess flow regulation services provided by wetlands. The combined use of HYDROTEL and ECCC's daily WBM were efficient in modeling discharge into the Richelieu River at the Rapid Fryers gauge station and water levels in Lake Champlain and Richelieu River (St. Jean Marina). The modelling framework is suitable to assess various water storage scenarios. It is noteworthy that the PHYSITEL and HYDROTEL integration of LCRR basin is readily available to potential users, mind you they would require basic training and software license. Last but not least, we would need to translate the GUI in English.

Existing wetlands play a key role in attenuating high flows and flooding and also amplifying low flows in the LCRR sub-watersheds. Thus wetlands affect daily Lake Champlain NBSs and water levels; governing water levels and discharges in the Richelieu River. The simulation results clearly 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. We found that increasing water storage to reduce flood within the LCRR basin provided a framework to at least quantify their hydrological services. The actual study focused on four exploratory (4) independent scenarios: (i) storing water on riparian agricultural landscapes; (ii) a first DEM-based wetland addition scenario; and (iii): USEPA high potential wetland scenario; and (iv) a combination of the last two wetland scenarios. All scenarios provided probative results in reducing high flows, improving lows flows, decreasing peak NBSs and discharges and decreasing water levels. However, wetland construction/restoration or flooding farmland (riparian agricultural land) would require extensive surface areas; raising feasibility and acceptability issues.

Table 11.1 presents the land cover involved in each scenario.

Table 11.1 Land cover involved in farmland water storage and wetland scenarios.

	Lake Champlain Basin				Richelieu River Basin (Fryers)			
Scenario	AGRI	WET DEM	EPA H	COMBINED	AGRI	WET DEM	EPA H	COMBINED
Total additional storage area	2256	647	865	1488	2471	649	865	1489
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	2256	43	294	332	2471	44	294	334
Others	-	17	104	121	-	17	104	121

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

Given existing policies, programs and regulations North (e.g., Quebec Bill 132 - An Act respecting the conservation of wetlands and bodies of water) and South (e.g., programs managed by the USDA Natural Resources Conservation Service and the USDA Fish and Wildlife Service, and Vermont and New York States Departments of Environmental Conservation) of the boarder; fostering restauration and construction of wetlands might find to be a socially-acceptable approach to build resilience over time in the LCRR basin, at least at the local sub-watershed level.

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. It is readily available and specific to this study and can be applied on any LCRR sub-watershed. For other watersheds, use of the tool would solely require integration of basic geographic layers such as DEM, lake and river networks, soil and land cover maps into PHYSITEL. In addition, the LCRR HYDROTEL modelling project is available to assess multiple scenarios for each sub-watershed, but ultimately for any scenario, there is need to conduct comprehensive studies, including: (i) 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 « *x* » and « *y* » cm in LC and RR, respectively; (ii) an assessment of the effect on low flows; and (iii) a cost-benefit analysis including total costs (e.g., construction, easement payments, …) and total benefits (e.g., avoided damages, valuing environmental goods and services…).

It is noteworthy, the outcomes of this study were presented at two IJC technical webinars held on November 5, 2020.

Finally, we would like to thank Olivier Champoux and Jean Morin of Environment and Climate Change Canada for their valuable technical inputs throughout the project with the quarterly and daily water balance models of Lake Champlain. Last but not least, we would like to acknowledge the scientific and administrative supports of Pierre-Yves Caux, Ted Yuzik and Bill Werick of the IJC, Serge Villeneuve and Jean-François Cantin of ECCC, Simon Lachance-Cloutier of the MELCC DEH, and Keith Robinson of the USGS New England Water Science.

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Appendix I. 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 parametrization was adapted to reflect the anticipated behaviour of flooded farmland. A schematic representation of the modules is presented in Figure A 1.

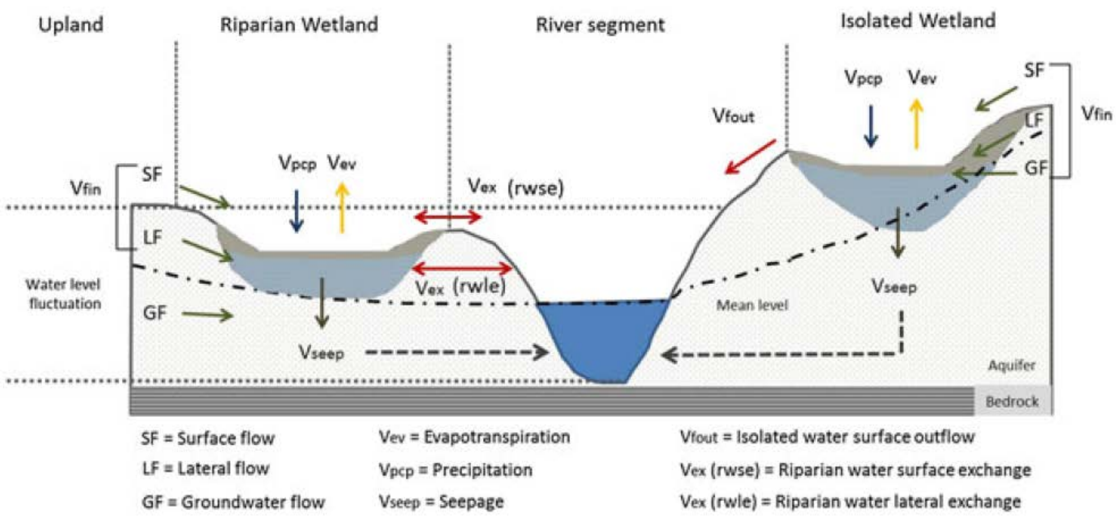


Figure A 1 Scheme of water exchanges through isolated or riparian wetlands (from Fossey et al., 2015).

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 presents all the equations and supporting algorithm 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 sub-watersheds (i.e., computational units - RHHUs) or average parameter values for RHHUs without exiting wetlands (see Table A 1). Such parameters are based on previous work and surveyed literature.

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

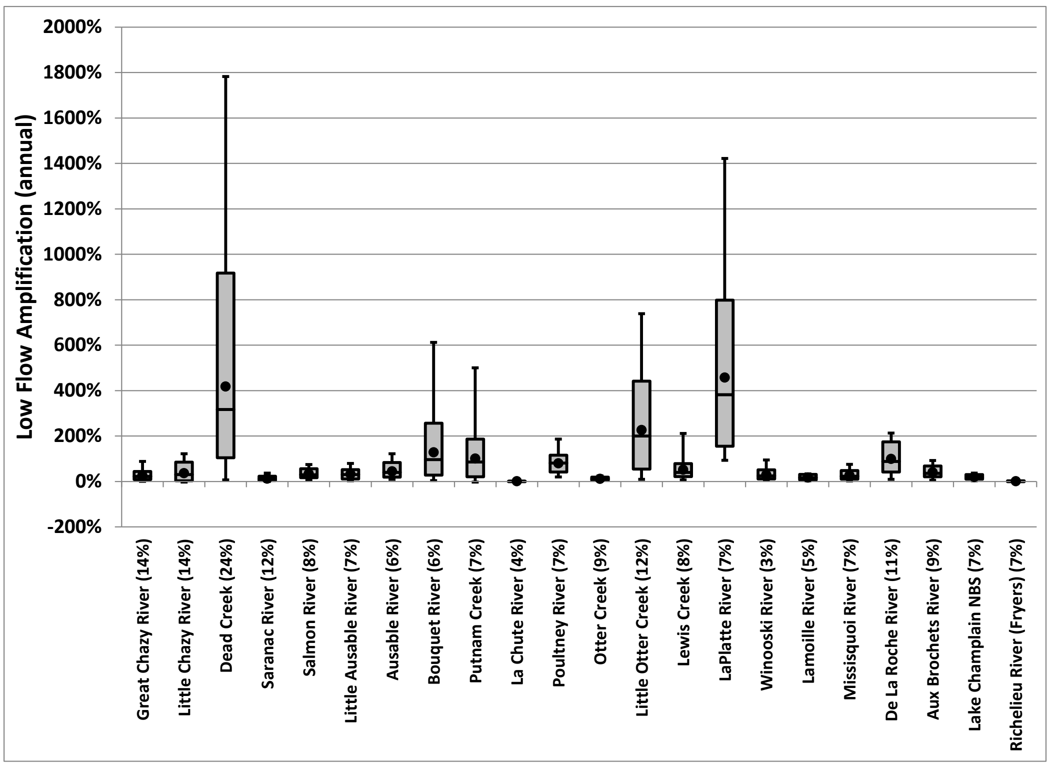
Type	Ratio (Normal Area / Maximal Area)	Normal water height (m)	Maximal water height (m)
Average wetlands	0.30	0.20	0.85

From a general point of view, wetlands intercept water and according to specific relationships govern release some. 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.

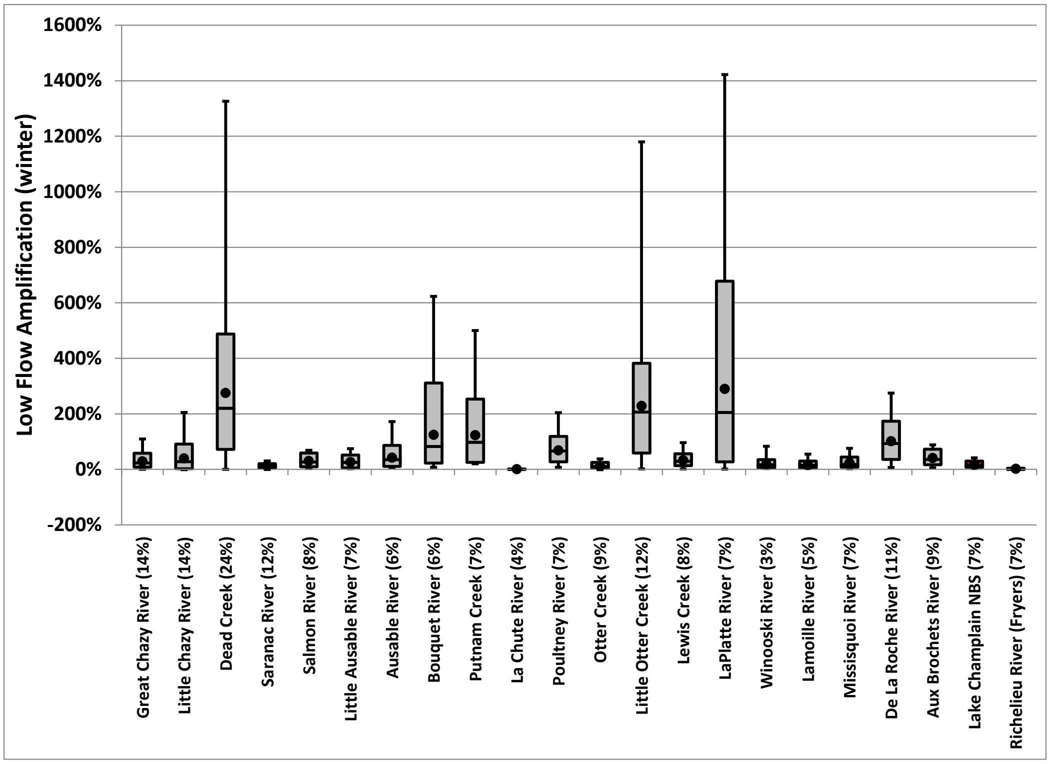
Appendix II. Impact of wetland and water storage scenarios on low flows

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.

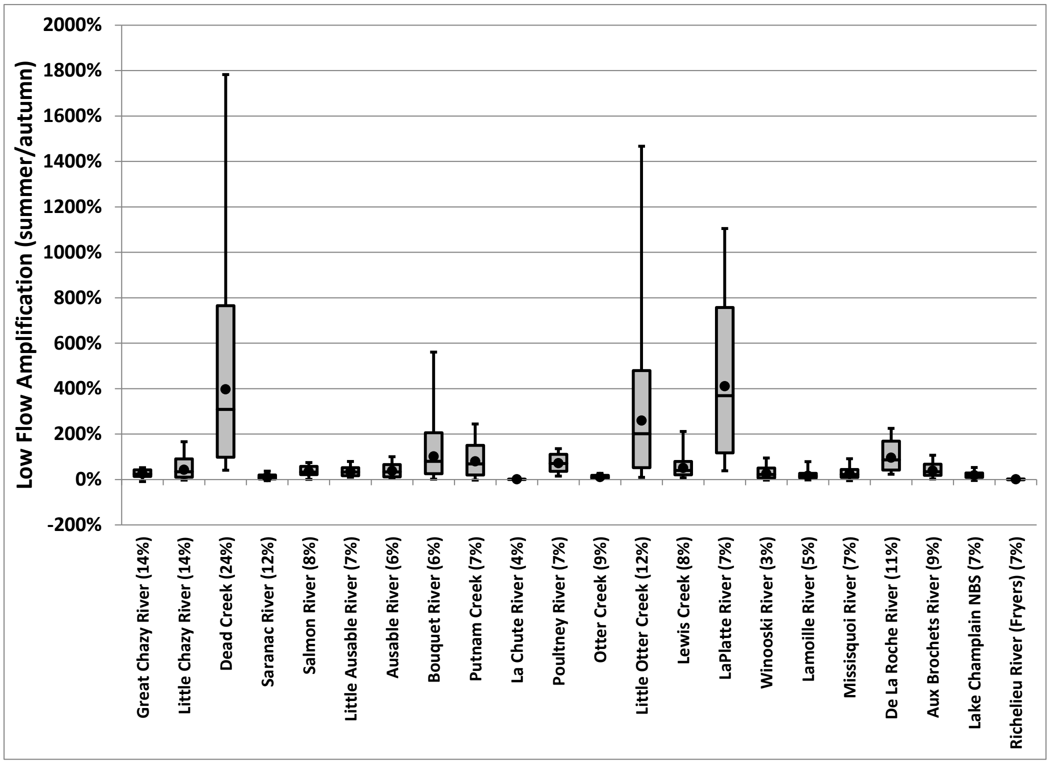
Current wetland distribution in the LCRR basin



(a)


Low Flow Amplification (winter)
1600%
1400%
1200%
1000%
800%
600%
400%
200%
0%
-200%
Great Chazy River (14%)
Little Chazy River (14%)
Dead Creek (24%)
Saranac River (12%)
Salmon River (8%)
Little Ausable River (7%)
Ausable River (6%)
Bouquet River (6%)
Putnam Creek (7%)
La Chute River (4%)
Poultney River (7%)
Otter Creek (9%)
Little Otter Creek (12%)
Lewis Creek (8%)
LaPlatte River (7%)
Winooski River (3%)
Lamoille River (5%)
Missisquoi River (7%)
De La Roche River (11%)
Aux Brochets River (9%)
Lake Champlain NBS (7%)
Richelieu River (Fryers) (7%)

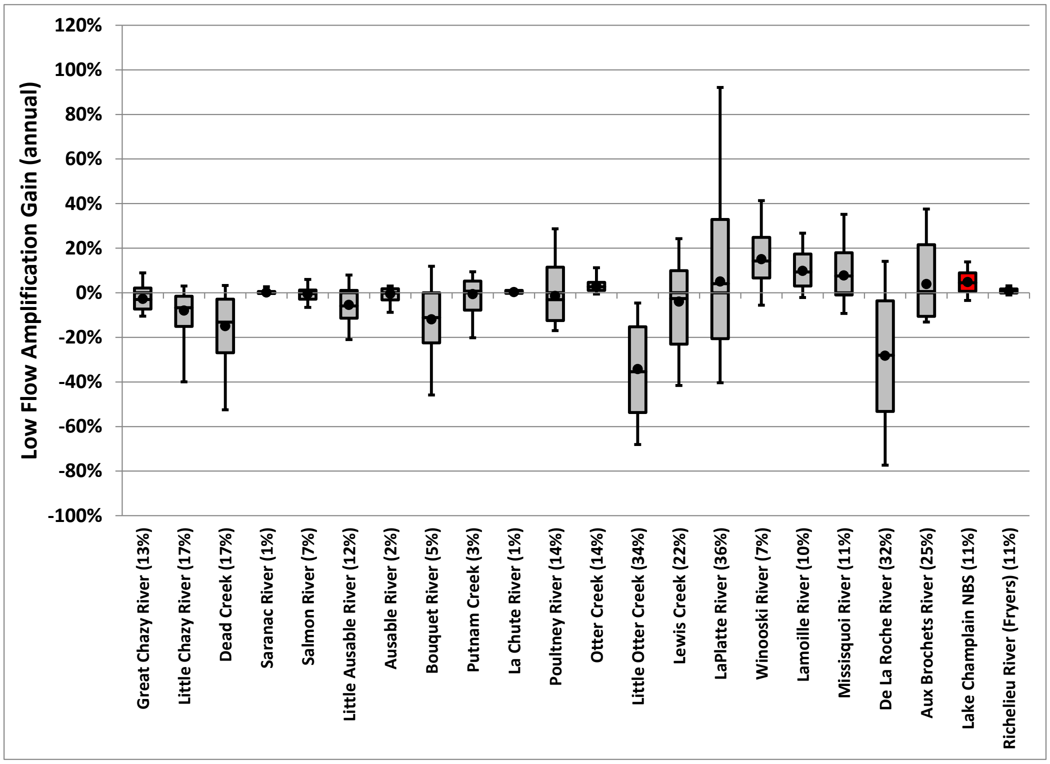
(b)



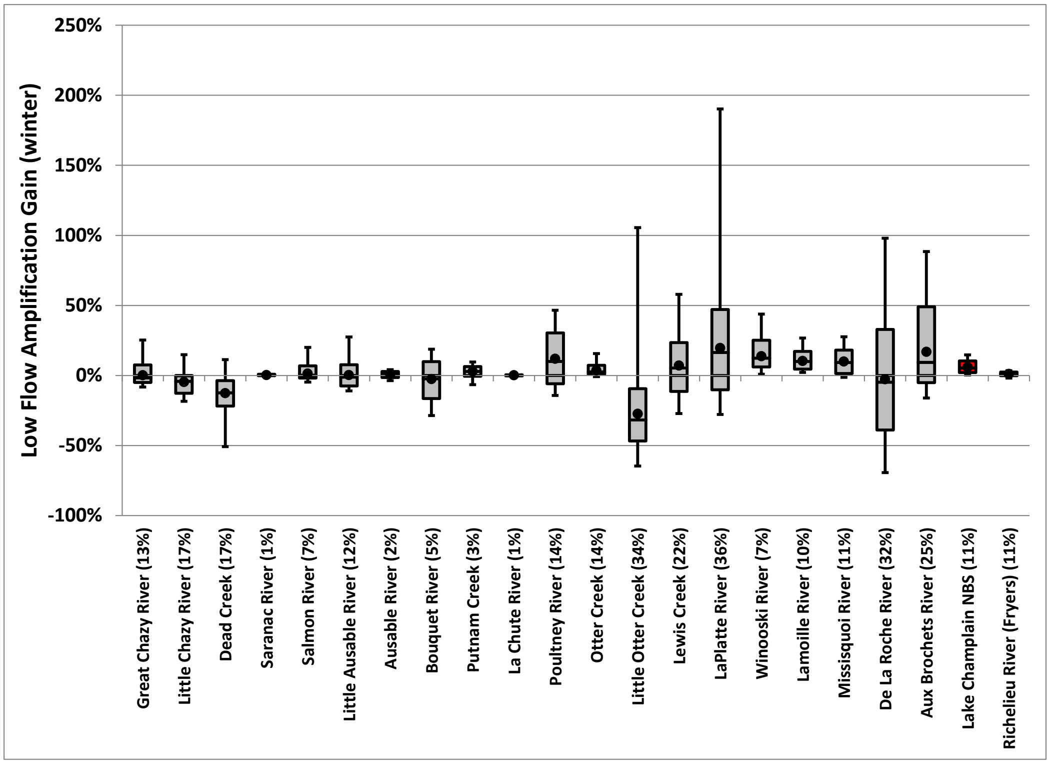
(c)

Figure A 2 Impacts of current wetlands on low flow amplification of the 20 LC sub-watersheds, LC NBS and RR flows at Rapid Fryers (Min; Max; 10th centile; 90th centile; Median; Average) for various temporal scales: (a) annual, (b) winter and (c) summer/fall.

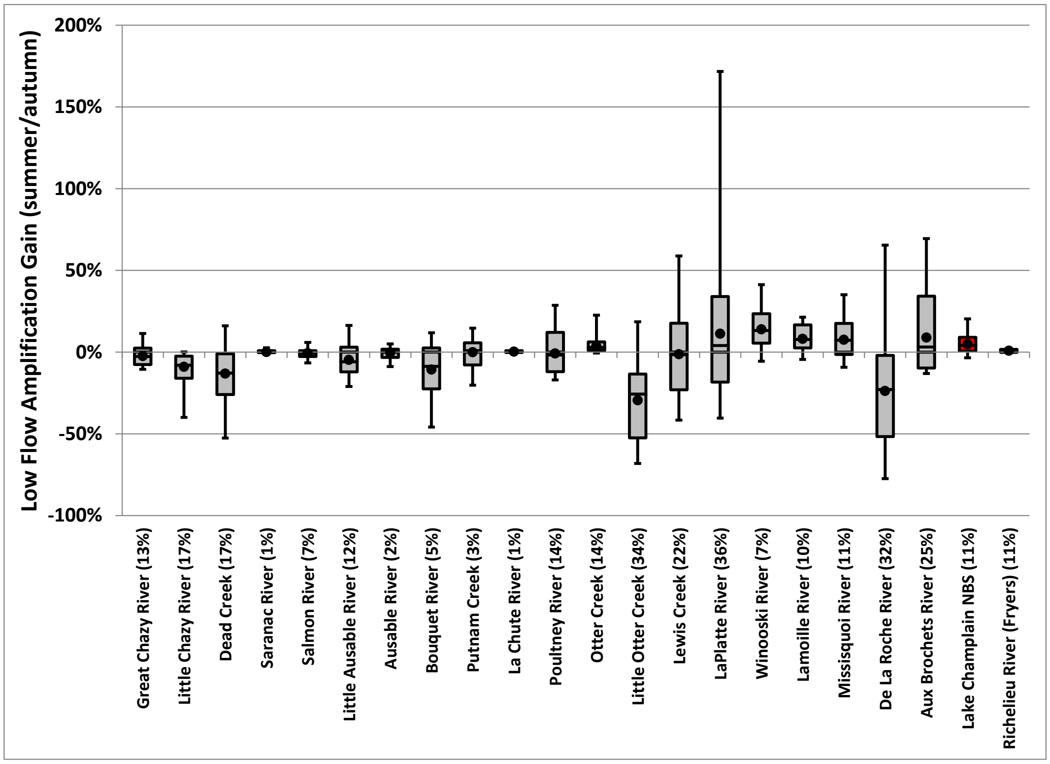
Riparian agricultural landscapes water storage scenario



(a)


250%
200%
150%
100%
50%
0%
-50%
-100%
Low Flow Amplification Gain (winter)
Great Chazy River (13%)
Little Chazy River (17%)
Dead Creek (17%)
Saranac River (1%)
Salmon River (7%)
Little Ausable River (12%)
Ausable River (2%)
Bouquet River (5%)
Putnam Creek (3%)
La Chute River (1%)
Poultney River (14%)
Otter Creek (14%)
Little Otter Creek (34%)
Lewis Creek (22%)
LaPlatte River (36%)
Winooski River (7%)
Lamoille River (10%)
Missisquoi River (11%)
De La Roche River (32%)
Aux Brochets River (25%)
Lake Champlain NBS (11%)
Richelieu River (Fryers) (11%)

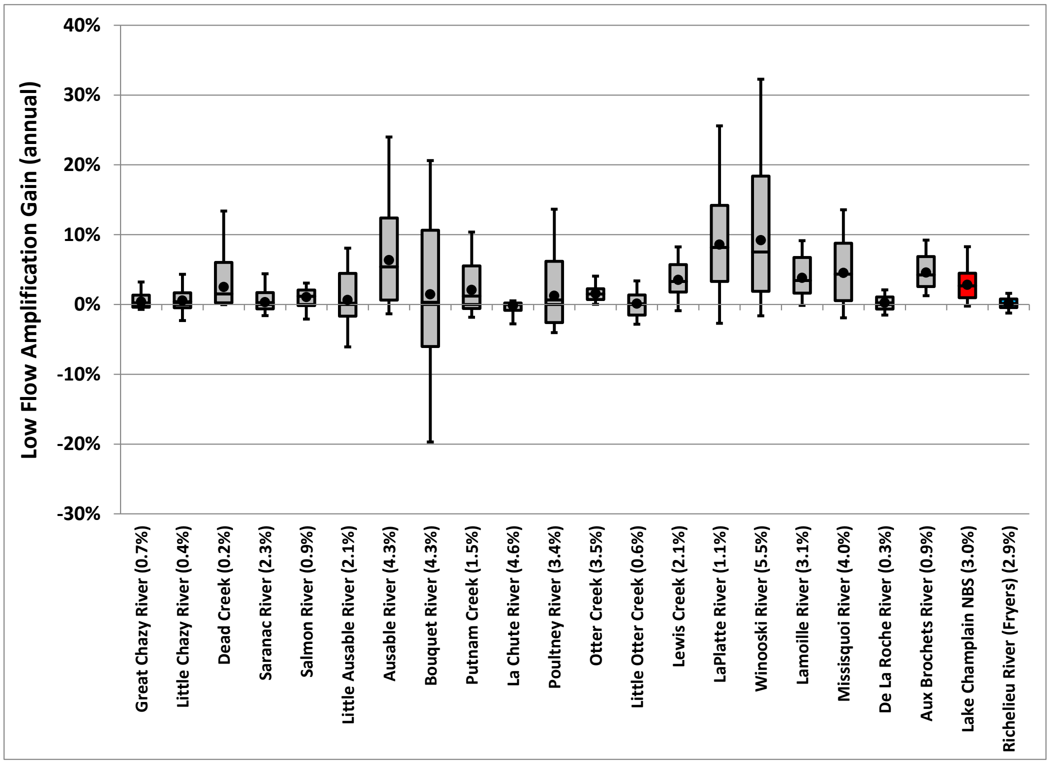
(b)



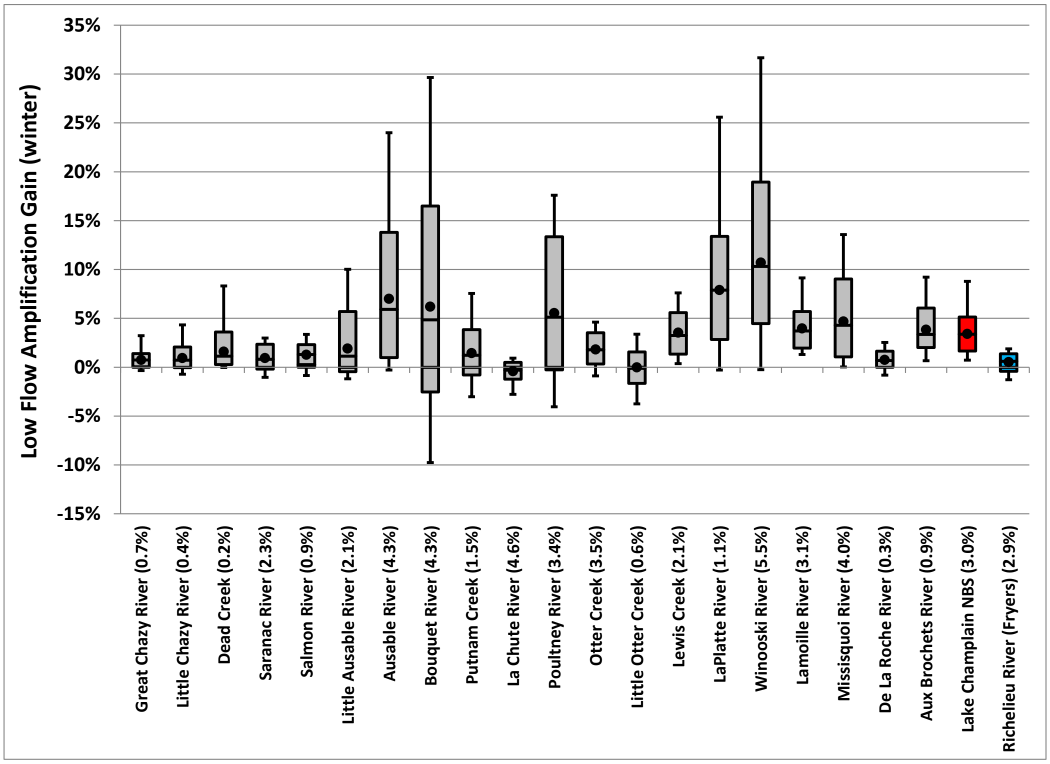
(c)

Figure A 3 Gains in low flow amplification (summer/fall) due to storing water on riparian agricultural landscapes of the LCRR basin for the 20 LC sub-watersheds, LC NBS and RR flows at Rapid Fryers with respect to current conditions (⊥ Min; T Max; 10th centile; 90th centile; Median; Average) for various temporal scales: (a) annual, (b) winter and (c) summer/fall.

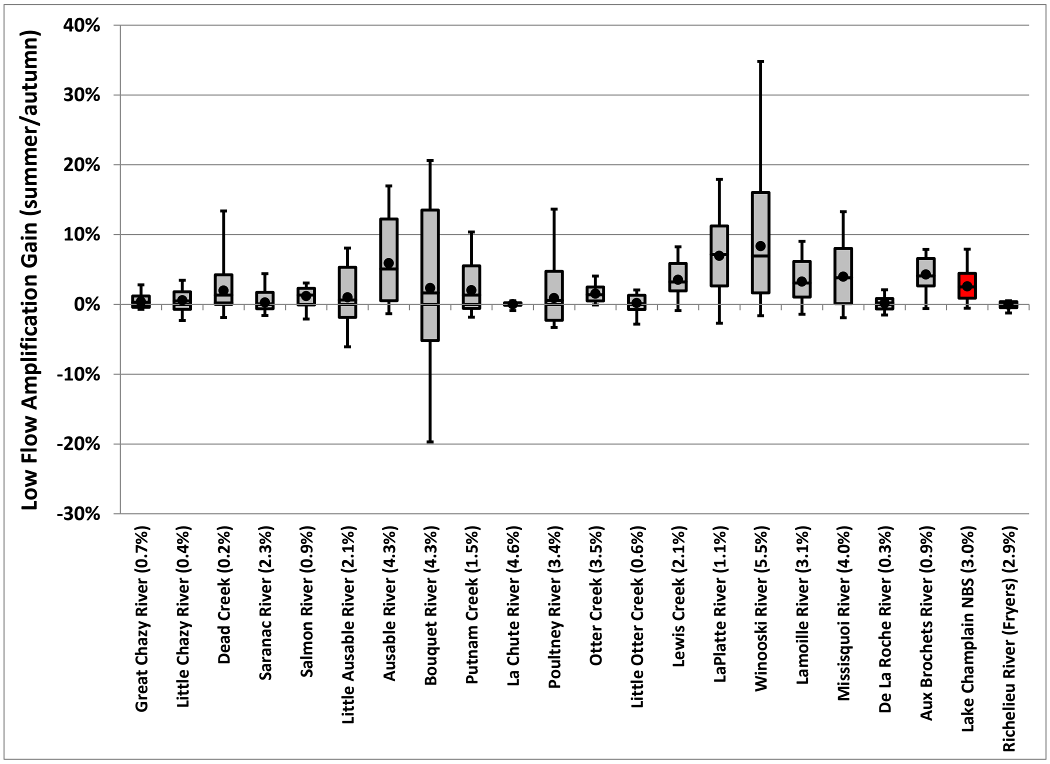
Wetlands construction/restoration scenario based on spatial data



(a)


Low Flow Amplification Gain (winter)
35%
30%
25%
20%
15%
10%
5%
0%
-5%
-10%
-15%
Great Chazy River (0.7%)
Little Chazy River (0.4%)
Dead Creek (0.2%)
Saranac River (2.3%)
Salmon River (0.9%)
Little Ausable River (2.1%)
Ausable River (4.3%)
Bouquet River (4.3%)
Putnam Creek (1.5%)
La Chute River (4.6%)
Poultney River (3.4%)
Otter Creek (3.5%)
Little Otter Creek (0.6%)
Lewis Creek (2.1%)
LaPlatte River (1.1%)
Winooski River (5.5%)
Lamoille River (3.1%)
Missisquoi River (4.0%)
De La Roche River (0.3%)
Aux Brochets River (0.9%)
Lake Champlain NBS (3.0%)
Richelieu River (Fryers) (2.9%)

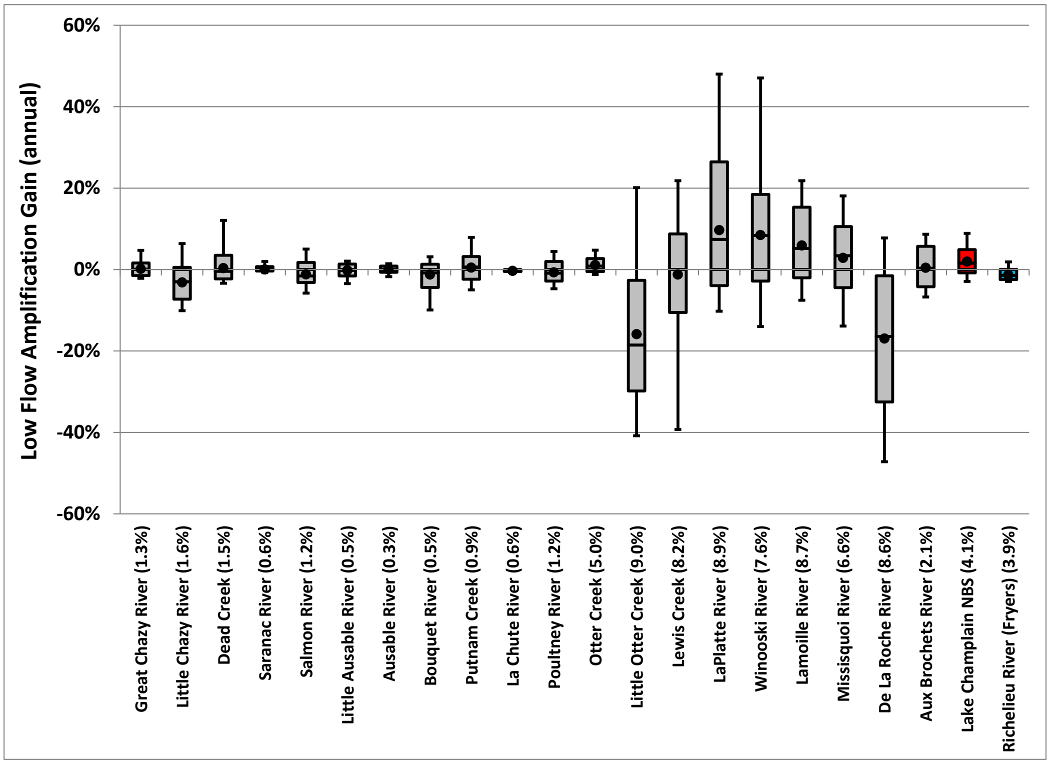
(b)



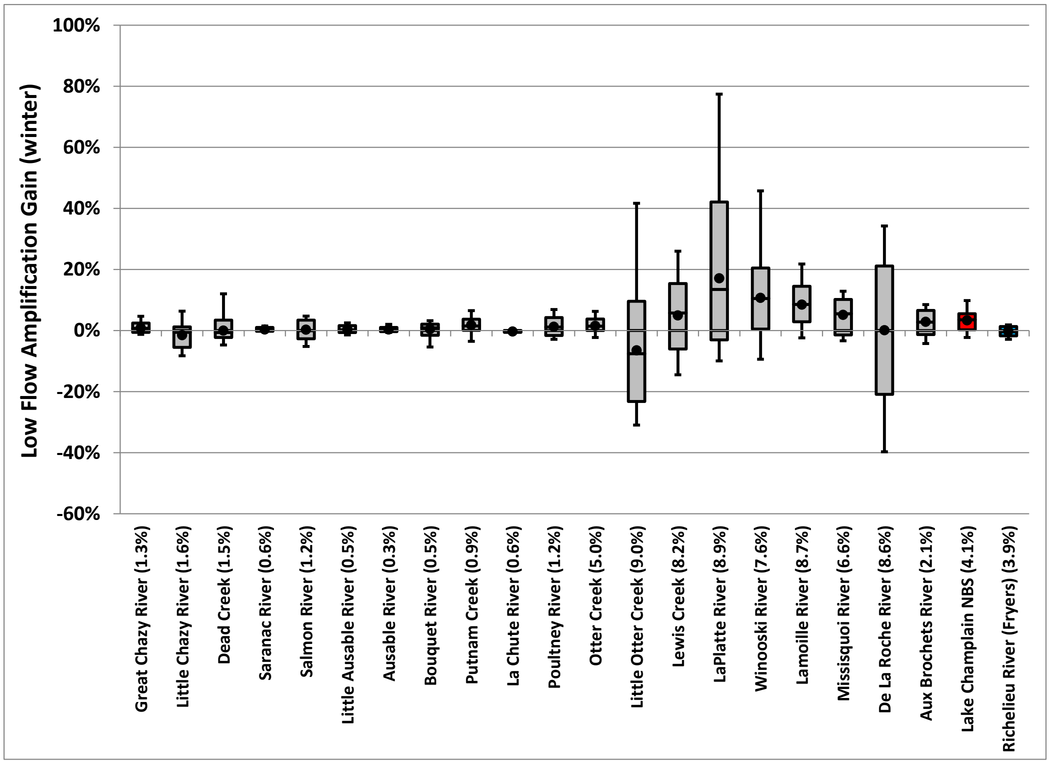
(c)

Figure A 4 Gains in low flow amplification (summer/fall) when adding 652 km^2 of wetland in the LCRR basin for the 20 LC sub-watersheds, LC NBS and RR flows at Rapid Fryers compare to current conditions (⊥ Min; T Max; ⊔ 10th centile; ⊓ 90th centile; ▬ Median; • Average) for various temporal scales: (a) annual, (b) winter and (c) summer/fall.

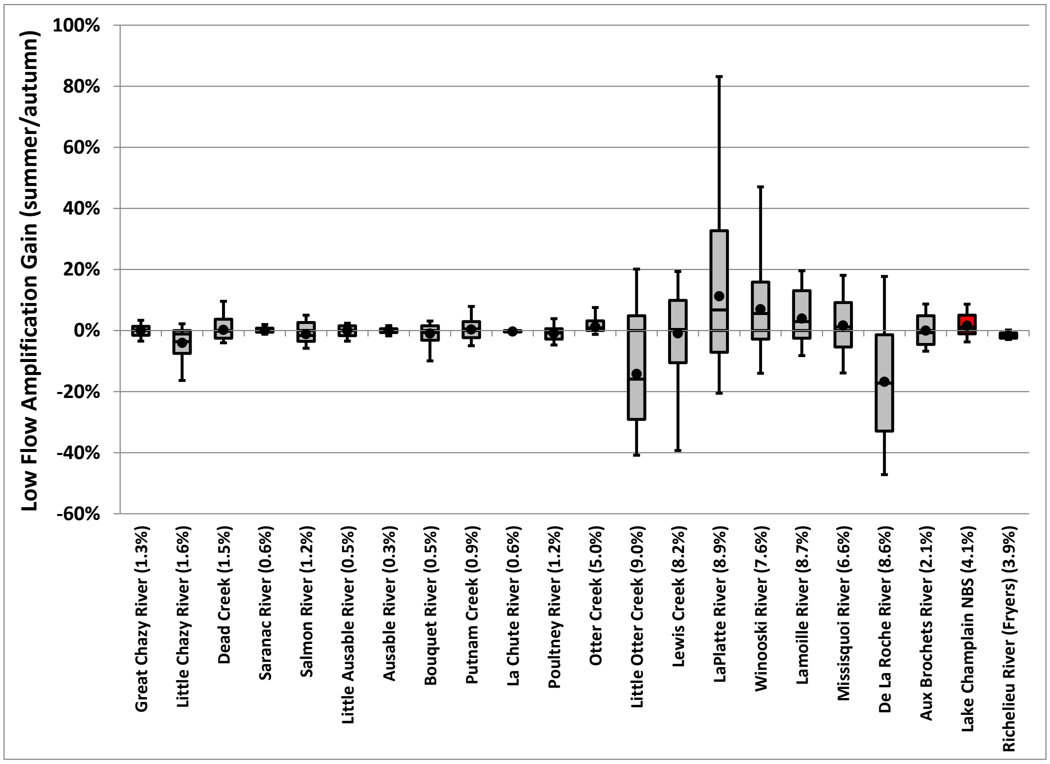
USEPA wetland scenario



(a)


Low Flow Amplification Gain (winter)
100%
80%
60%
40%
20%
0%
-20%
-40%
-60%
Great Chazy River (1.3%)
Little Chazy River (1.6%)
Dead Creek (1.5%)
Saranac River (0.6%)
Salmon River (1.2%)
Little Ausable River (0.5%)
Ausable River (0.3%)
Bouquet River (0.5%)
Putnam Creek (0.9%)
La Chute River (0.6%)
Poultney River (1.2%)
Otter Creek (5.0%)
Little Otter Creek (9.0%)
Lewis Creek (8.2%)
LaPlatte River (8.9%)
Winooski River (7.6%)
Lamoille River (8.7%)
Missisquoi River (6.6%)
De La Roche River (8.6%)
Aux Brochets River (2.1%)
Lake Champlain NBS (4.1%)
Richelieu River (Fryers) (3.9%)

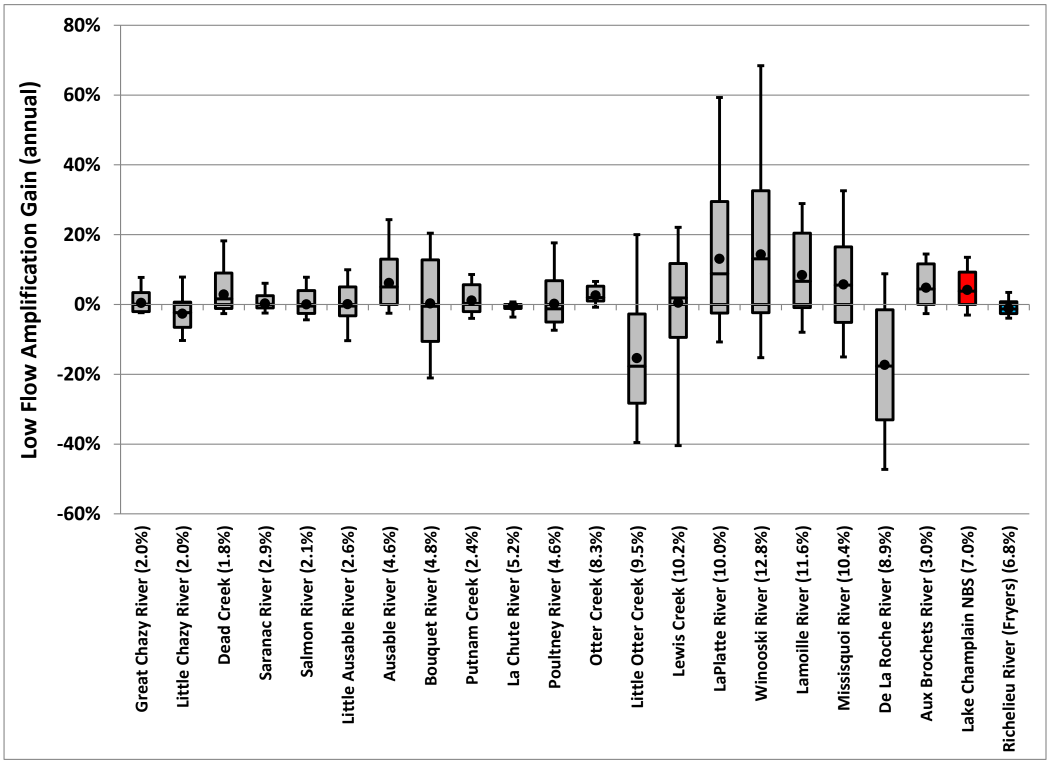
(b)



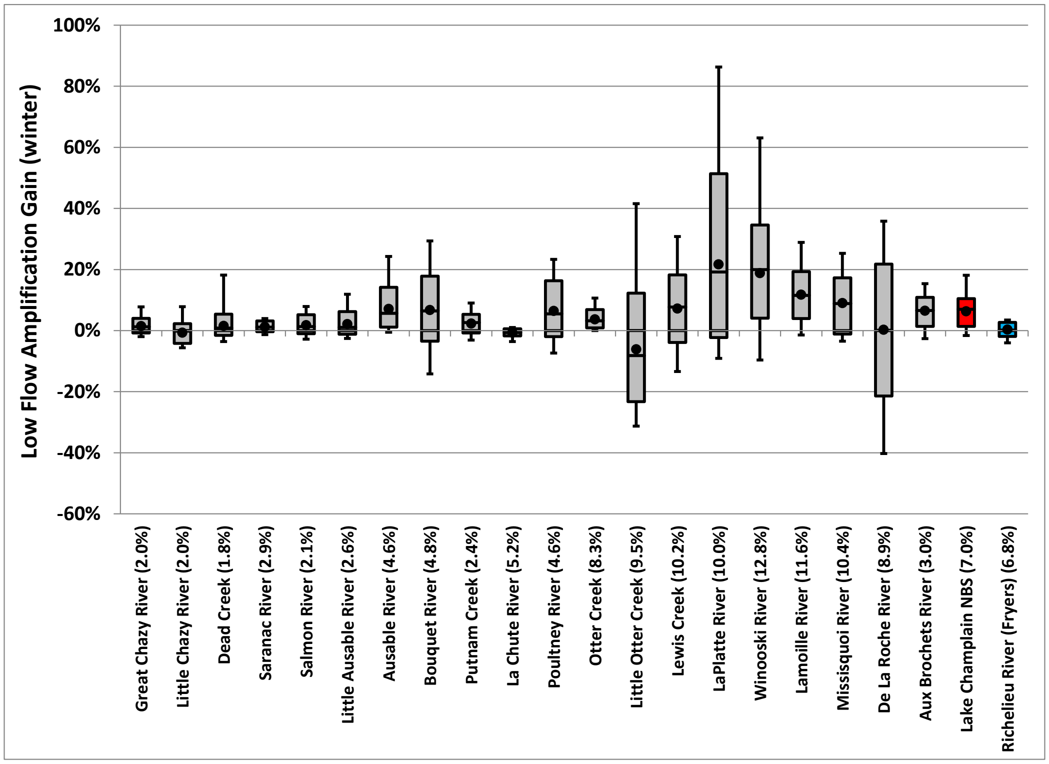
(c)

Figure A 5 Gains in low flow amplification (summer/fall) of the USEPA wetland scenario on the LCRR basin for the 20 LC sub-watersheds, LC NBS and RR flows at Rapid Fryers compare to current conditions (⊥ Min; ⊤ Max; 10th centile; 90th centile; Median; Average) for various temporal scales: (a) annual, (b) winter and (c) summer/fall.

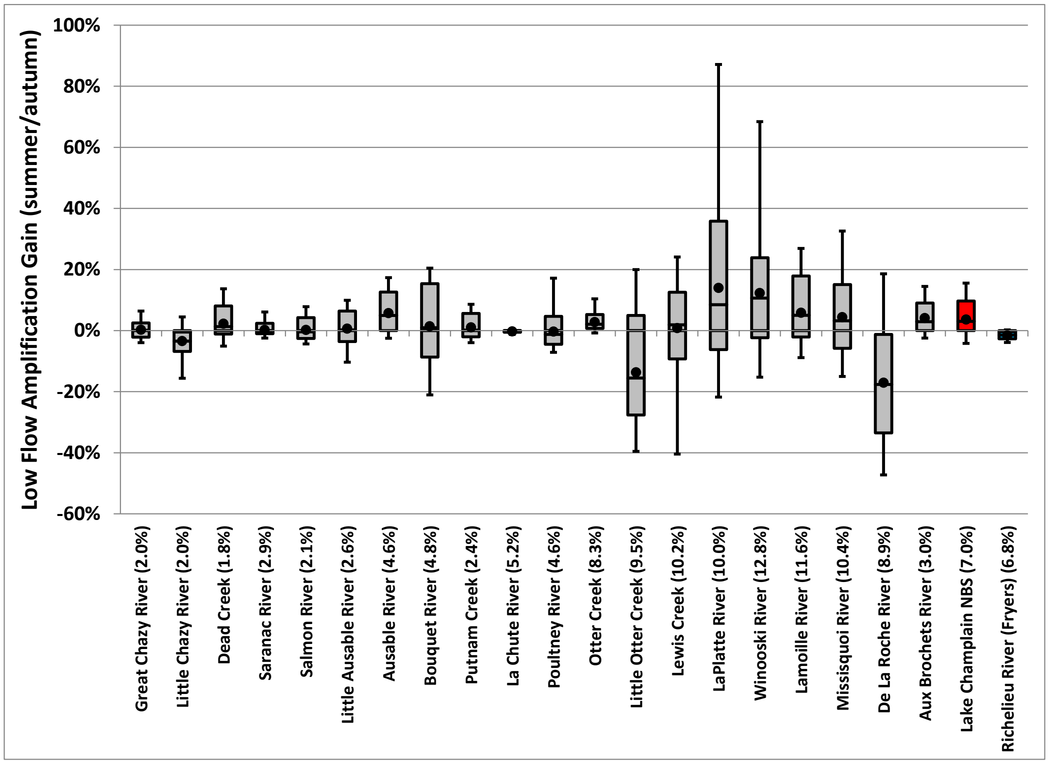
Combined wetland scenario



(a)


Low Flow Amplification Gain (winter)
100%
80%
60%
40%
20%
0%
-20%
-40%
-60%
Great Chazy River (2.0%)
Little Chazy River (2.0%)
Dead Creek (1.8%)
Saranac River (2.9%)
Salmon River (2.1%)
Little Ausable River (2.6%)
Ausable River (4.6%)
Bouquet River (4.8%)
Putnam Creek (2.4%)
La Chute River (5.2%)
Poultney River (4.6%)
Otter Creek (8.3%)
Little Otter Creek (9.5%)
Lewis Creek (10.2%)
LaPlatte River (10.0%)
Winooski River (12.8%)
Lamoille River (11.6%)
Missisquoi River (10.4%)
De La Roche River (8.9%)
Aux Brochets River (3.0%)
Lake Champlain NBS (7.0%)
Richelieu River (Fryers) (6.8%)

(b)



(c)

Figure A 6 Gains in low flow amplification (summer/fall) of the combined wetland scenarios on the LCRR basin for the 20 LC sub-watersheds, LC NBS and RR flows at Rapid Fryers compare to current conditions (Min; Max; 10th centile; 90th centile; Median; Average) for various temporal scales: (a) annual, (b) winter and (c) summer/fall.