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

2019-2020 Progress Report submitted to:

Environment and Climate Change Canada

International Joint Commission

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Report N° R1925

March 2020

ISBN : 978-2-89146-944-9 (version électronique)
Dépôt légal - Bibliothèque et Archives nationales du Québec, 2021
Dépôt légal - Bibliothèque et Archives Canada, 2021

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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 peak 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 is to assess the effect of passive and active approaches of flood mitigation methods in the LCRR watershed; that is assessing the potential: (i) reduction in runoff volumes and peak flows provided by current, restored, and constructed wetlands of tributaries of the watershed and (ii) storage of flood water on riparian agricultural landscapes.

Completed 2019-2020 tasks

Here is a brief description of the tasks completed during the April 2019 to Marsh 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

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

6. Development of a simplified approach to design wetlands construction/restoration scenarios.

7. Evaluation of a conservative wetland construction/restoration scenario.

8. Preliminary back-of-the-envelope assessment of the additional surface area of wetlands and farmland required to reduce the peak flow of the 2011 flood flow.

9. Drafting of the Watershed Storage Progress report.

[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).

3 Materials and methods

This project is supported by five major activities namely:

(i) Adapting the current implementation of HYDROTEL - 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 is important to start with the same database, but there is 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 and then calibrate and validate HYDROTEL using an optimization software tool (OSTRICH).

(iii) Construction of various wetlands construction/restoration scenarios using a priori a simplified approach based on topographical data (i.e., DEM).

(iv) Using HYDROTEL, assessment of the potential reduction in runoff volumes and peak flows provided by current wetlands distributions as well constructed or restored wetlands scenarios of all the major tributaries of the LCRR sub-watersheds.

(v) Evaluation of the potential water storage on agricultural land using the DEM of the major tributaries of the LCRR watershed to construct with PHYSITEL various scenarios to direct water towards agricultural land away from areas to be protected.

(vi) Using the HAND algorithm (Nobre et al., 2016) implemented in PHYSITEL and HYDROTEL, assessment of the potential storage of flood water on riparian agricultural landscapes provided by the developed scenarios or other approaches.

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 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 benefit from 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 requires 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 wetlands attributes based on existing inventory maps.

Table 4.1 presents the information required for 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)

The following figures show maps of the input data introduced in Table 4.1.

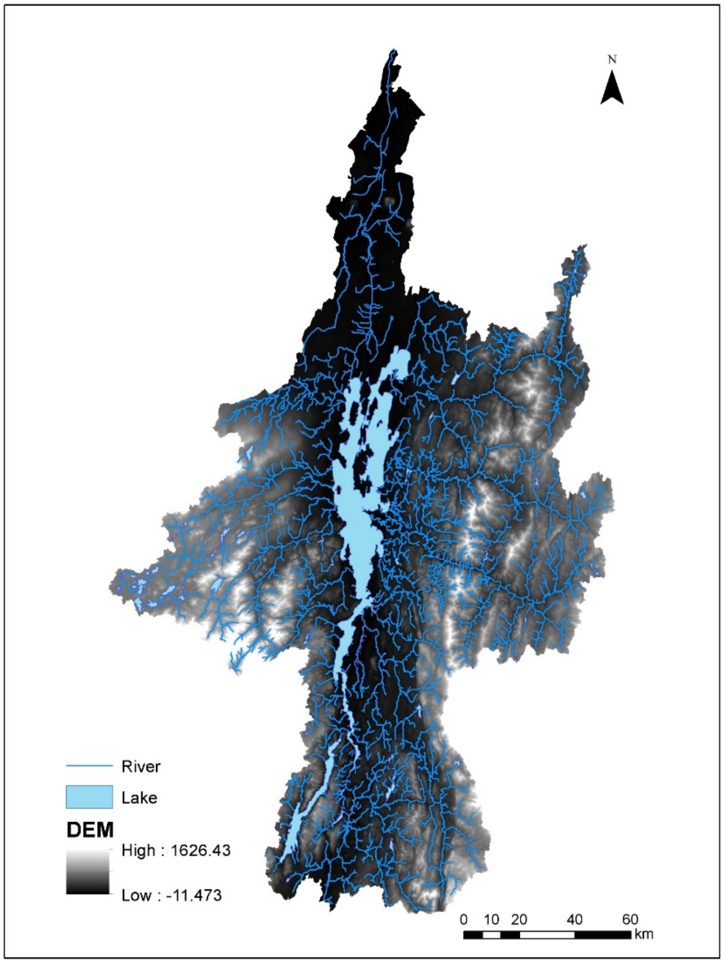

Figure 4.1 Digital elevation model (DEM) and stream and lake network.

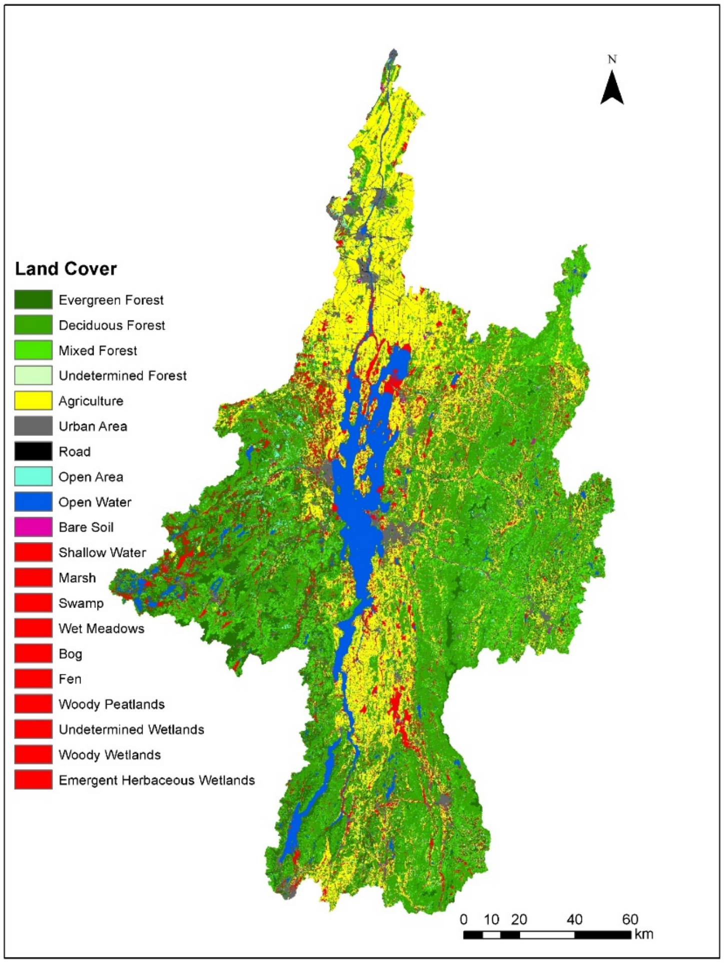

Figure 4.2 Land cover and wetlands inventory.

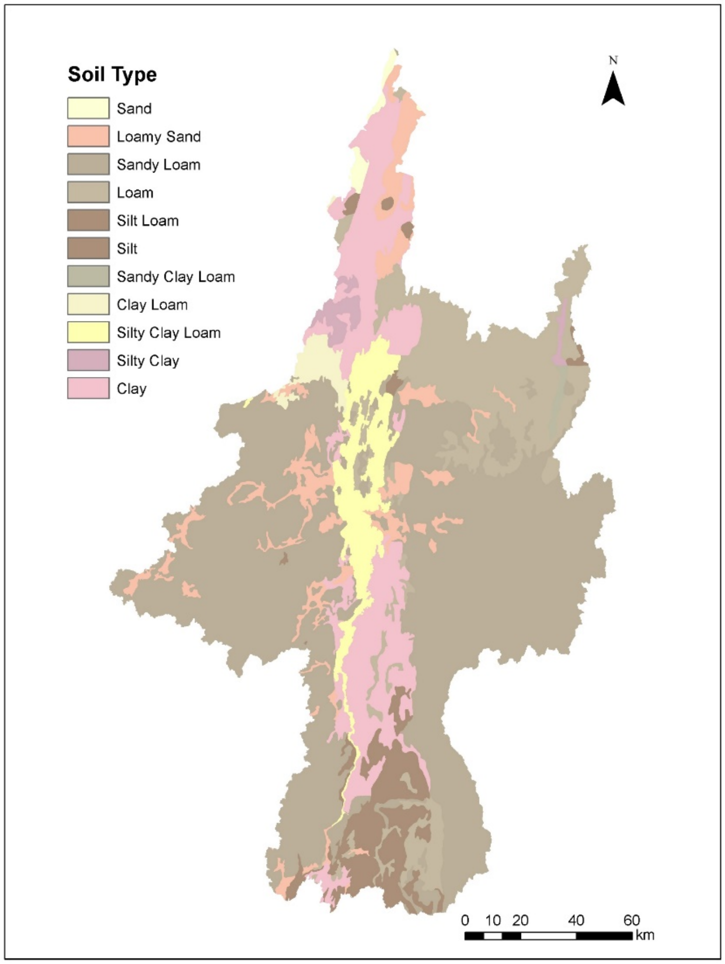

Figure 4.3 Soil type.

Additional data requirement for hydrological modelling include: (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 delineates the watershed into Relatively homogenous hydrological units (i.e., namely hillslopes a.k.a, RRHU) and river/lake segments which constitute the computation 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 calculates a topographic index and identifies the dominant soil type, and percentages of different land covers. Figure 4.4 summarizes the various tasks performed by PHYSITEL.

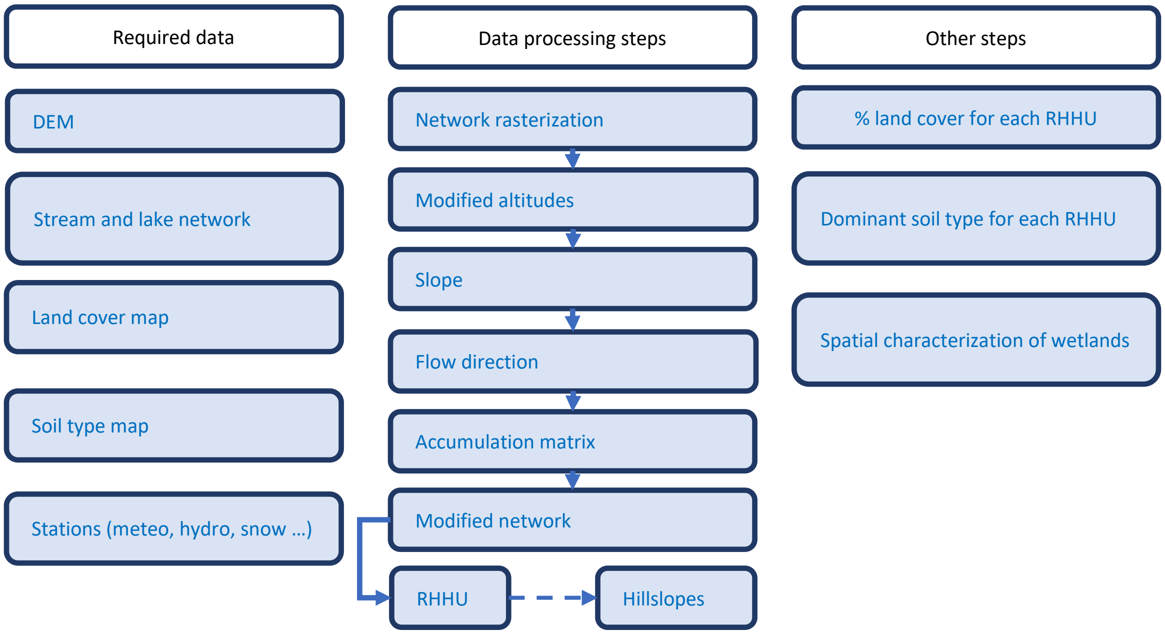

Figure 4.4 PHYSITEL – Input data and data processing.

As indicated, PHYSITEL allows 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 identifies isolated and riparian (based on a river connectivity threshold) and drainage area of each type of wetlands.

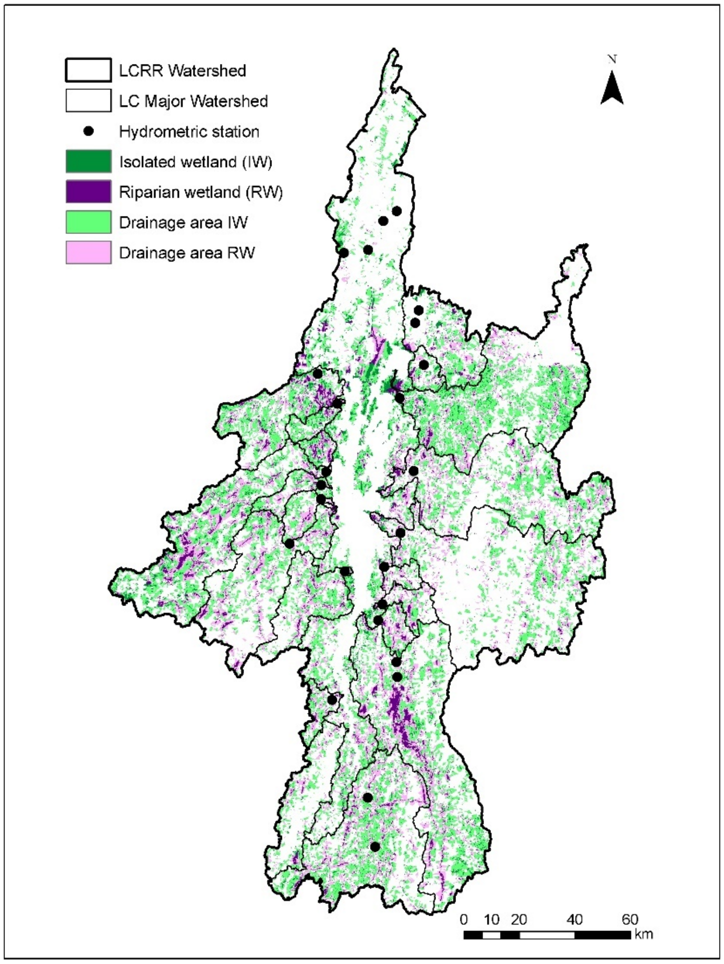

Figure 4.5 Drainage area and types (isolated and riparian) of wetlands in the LCRR watershed.

As a complement, Table 4.2 introduces the 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 (km^2) (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 (7.1%)	1551 km^2 (7.3%)
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	1684 km^2 (7.1%)	7749 km^2 (36.5%)

It is noteworthy that, in terms total watershed area, the cumulative wetlands surface area and drainage area of the LC and LCRR watersheds are 7% and 34%, respectively; illustrating that 92% of wetlands are located within the USA.

5 HYDROTEL calibration and validation

From a hydrological modelling perspective, HYDROTEL (Fortin et al., 2001; Turcotte et al., 2003, 2007; Fossey et al., 2015) simulates evapotranspiration, snow accumulation/melt, infiltration, recharge, surface flow, subsurface flow and channel routing using a daily time step for this study.

HYDROTEL provides specific modules to simulate the hydrological processes of each type of wetland (isolated, riparian) that account for the water budget as 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 exchange and interaction with the adjacent river segment through overland runoff and river bank flow.

The hydrometeorological data include gridded or site-specific precipitation, 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 is made 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.

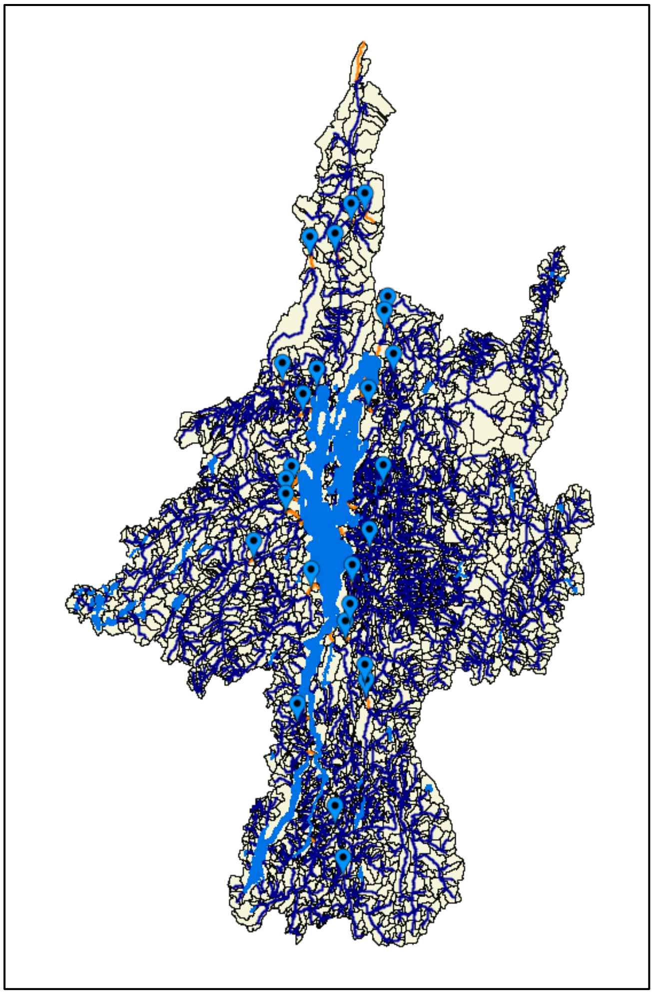

Figure 5.1 LCRR project of HYDROTEL.

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).

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 was based on 25 hydrometric stations (18 USGS, 6 DEHAQ, 1 FGC) within the LC sub-watershed and LCRR watershed. Weekly mean net basin supply (NBS) are also available for Lake Champlain.

Model calibration was 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 better represent flow observations. 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.

The calibration was performed automatically using the Optimization Software Toolkit for Research Involving Computational Heuristics (OSTRICH) – 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 station within the boundaries of the LCRR watershed.

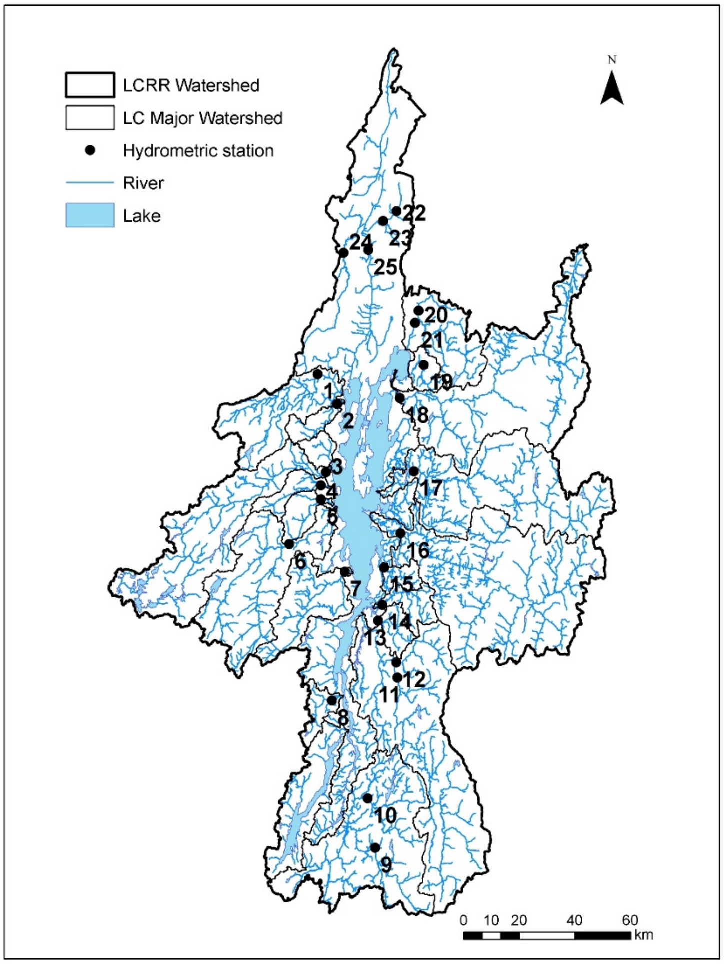

Figure 5.2 Location of the 25 hydrometric stations within the LCRR watershed.

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	0.83	2004-2013	0.90

For most of the sites and sub-watersheds with observations, results are deemed satisfactory as larger 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 passing from 082 to 0.76). For the SALMON, AUSABLE, DE LA ROCHE and À L’OURS sub-watersheds, the performance decreases more drastically for the validation period while other sub-watersheds such as the BOUQUET and LITTLE OTTER CREEK display an increase in performance. On the other hand, results at Rapid Fryer on the Richelieu River, downstream of Lake Champlain, are very good for both calibration and validation, improving in the latter period.

To further investigate model performance, simulation results were compared with observed stream flows using three approaches: (i) , the sum of observations, namely sub-watersheds 1 to 18 as identified on Figure 5.2; which essentially correspond to flows entering Lake Champlain (see first rows of Figures 5.3 and 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 weekly time step (second row of Figures 5.3 and 5.4). The NBS is made of inflows from all rivers discharging into Lake Champlain, precipitation over the lake, and lake evaporation and (iii) comparison of simulated and observed Richelieu River flows, downstream of Lake Champlain, at Fryers station (see last rows of Figures 5.3 and 5.4).

Sum of river flows of the 18 sub-watersheds of Lake Champlain

Lake Champlain NBS

River flows at Fryers

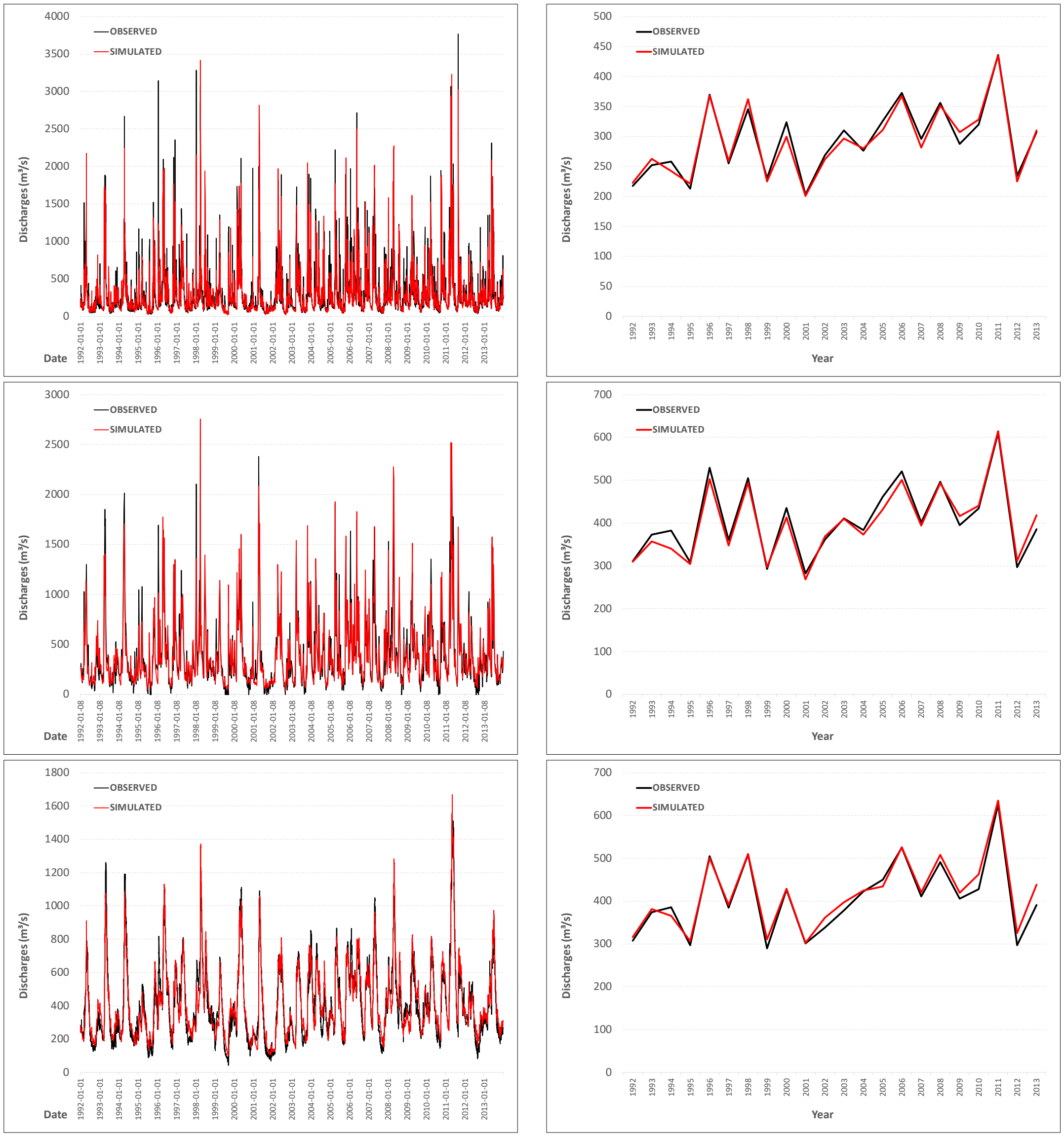

Figure 5.3 Daily (left column) and annual (right column) time series (1992-2013) of the sum of the river flows of the 18 Lake Champlain sub-watersheds (top row), the Lake Champlain NBS (center row) and the Richelieu river flows at Fryers station (bottom row). Observations are displayed in black and simulations in red.

Sum of river flows of the 18 sub-watersheds of Lake Champlain

Lake Champlain NBS

River flow at Fryers

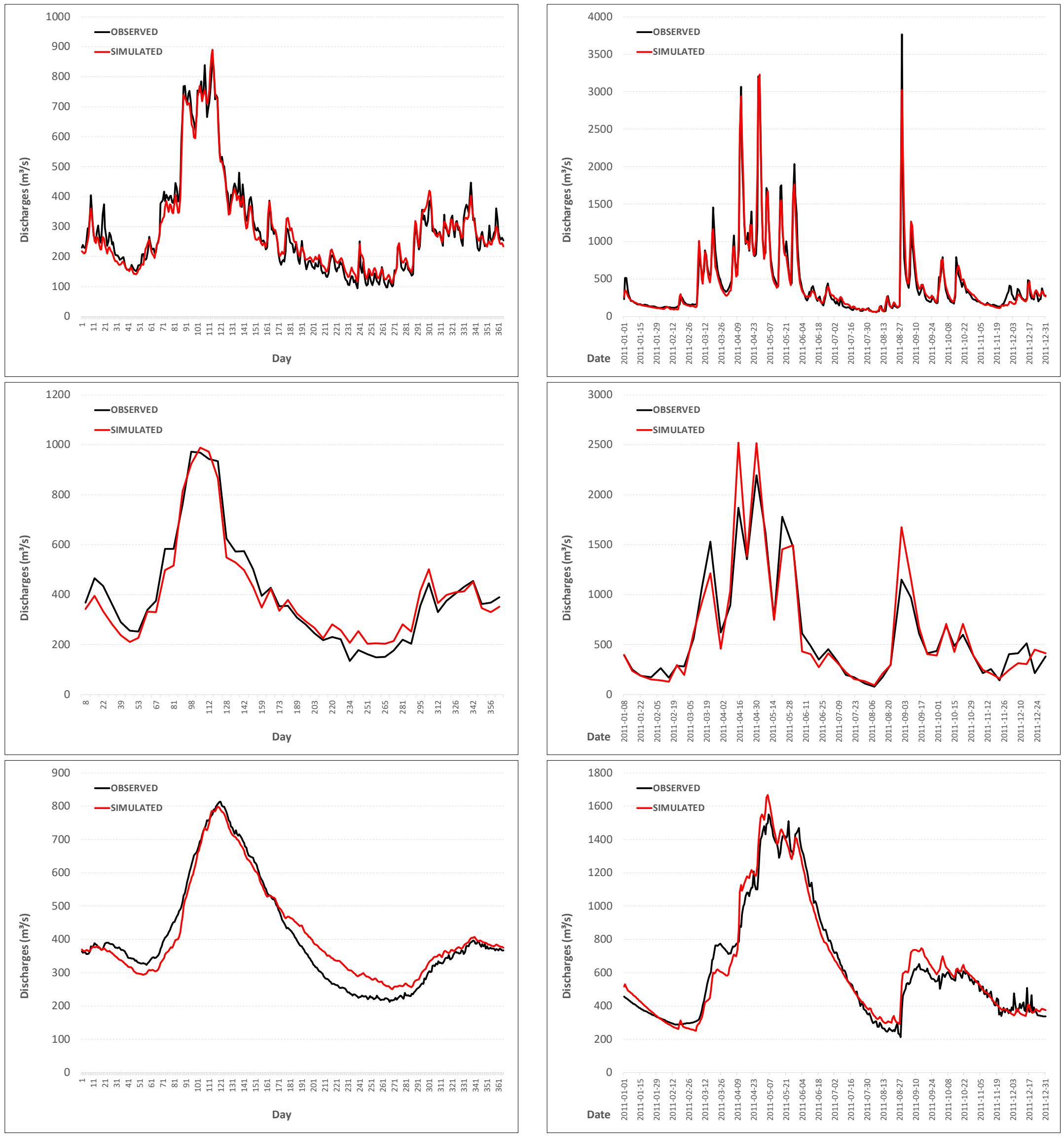

Figure 5.4 1992-2013 average annual hydrograph (left column) and 2011 hydrograph (right column) of the sum of river flows of the 18 gauged Lake Champlain sub-watersheds (top row), the of Lake Champlain NBS (center row) and the Richelieu river flows at Fryers station (bottom row). Observations are displayed in black and simulations in red.

Looking to 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 0.91 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 interannual variations of the sum-18 are also well simulated by HYDROTEL with a KGE value of 0.98 corresponding to a -1% 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 0.91 (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 well by HYDROTEL. Specific to year 2011, a KEG value of 0.96 and nearly null 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 weekly time step with a KGE value of 0.93. Again, the interannual variations are well represented with a KGE value of 0.94 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 0.86, but for 2011 the KGE value drops to 0.73. The simulated average annual hydrograph of NBSs shows an underestimation during the high flow period of April and May, while the average low flow is slightly overestimated in August and September. In Figure 5.4, the simulated peaks of the weekly time series of NBSs are sometimes underestimated or overestimated and explain the drop in the KGE value.

To complete the comparison, the simulated and observed Richelieu River flows, downstream of Lake Champlain, at Fryers station are compared. The KGE value of the 1992-2013 daily time series (bottom left graph of Figure 5.3) is slightly smaller than those for the sum-18 and the NBS with a value of 0.88 and a bias of +7.8%. Positive bias seems to be induced by an overestimation of the summer and fall flows by the model. This could be partly explained by an underestimation of lake evaporation and/or an underestimation of evapotranspiration across the watershed – this will need to be investigated. Nonetheless, the interannual variations of the annual average are still well simulated by HYDROTEL with a KGE value of 0.93 (bottom right graph of Figure 5.4). For the average annual hydrograph at Fryers station (bottom left graph of Figure 5.4), the average freshet in April and May is slightly underestimated by HYDROTEL and the average late-summer low flows in August and September are overestimated. Considering those differences, the KGE value of 0.79 for the average annual hydrograph and 0.96 for

2011 (bottom right graph of Figure 5.4) are still acceptable and generally viewed as good. Considering the 2011 flood, HYDROTEL slightly overestimated the observed peak flow of 1550 m^3/s by 88 m^3/s in early May at Fryers station. Simulated flows at Fryers station remains a challenge due to the upstream Lake Champlain water storage and routing effect. This will need to look into, although it is important to remember that effects of wind on observed flows are not simulated by HYDROTEL.

Finally, additional uncertainties can be linked to the gridded meteorological forcing and the other simulated flow tributaries of the Lake Champlain or the Richelieu River that were not calibrated because of 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 team (e.g., Fossey et al. 2015, 2016a,b,c, and Blanchette et al. 2019).

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 the wetland modules turned off. Without the wetland module, wetlands behave more like saturated soils, without any buffering capacity. Both 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.

To quantify the high flow attenuation services, we calculated, based on a continuous long term hydrological simulation covering years 1950 to 2013, the average attenuation of the 2-, 20- and 100-year annual maximum flows (Q2, Q20, Q100); while the low flow amplification services were assessed by calculating the average regulation of annual 7-day low flow with 2- and 10-year return periods (Q2-7, Q10-7) and 30-day low flow with a 5-year return period (Q5-30) (see Table 6.1 for an example). Based on the lowest Bayesian information criterion (BIC), we used the lognormal distribution to estimate the different return periods of high and low flows.

Table 6.1 Example of high flow attenuation and low flow amplification for the Great Chazy River watershed.

Indicator	High flow (m^3/s)				Low flows (m^3/s)			
	Q2	Q20	Q100		Q2-7	Q10-7	Q5-30	
Without wetlands	155.6	231.9	391.2		0.81	0.44	0.86	
With wetlands	94.8	137.5	238.3	**Average**	1.05	0.53	0.95	**Average**
Attenuation/Amplification	-39%	-41%	-39%	**-40%**	30%	19%	11%	**20%**

At first Figure 6.1 illustrates effect of the current distribution of wetlands in the LCRR watershed on 2011 annual hydrograph.

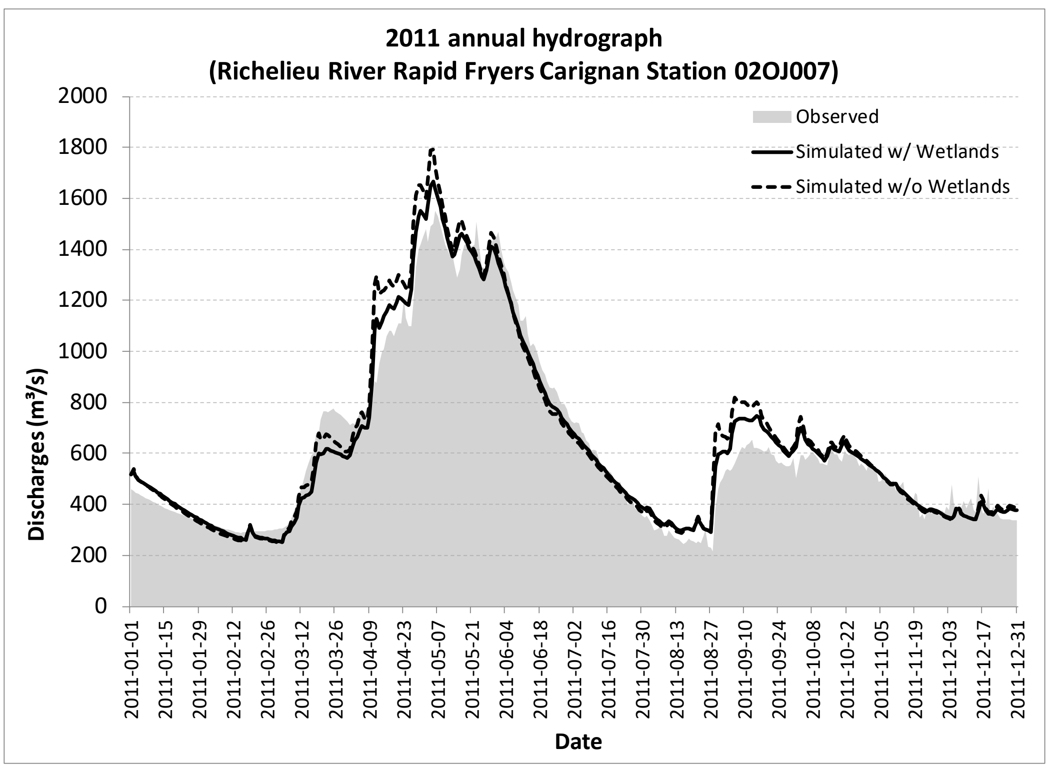

Figure 6.1 2011 annual hydrograph comparison of observed flows on the Richelieu River at Fryers station and simulated flows with and without the current distribution of wetlands.

AS mentioned before certain discrepancies can be observed between observed and simulated flows, but with overestimated spring and fall peak flows, but nonetheless, considering the challenges of reproducing the flows of the LCRR watershed, the 2011 year is satisfactorily achieved. That being mentioned, the simulations have provided a mean of assessing the flow regulation services of wetlands during the spring peak (7%) and fall peak fall (7%). The results show that wetlands tend to slightly decrease the flows on the rising limb of the spring freshet, while the opposite tend occur on the recession limb.

Figure 6.3 presents the 20 major gauged and ungauged sub-watersheds of the LC watershed while Table 6.2 highlights the impact of the current distribution of wetlands on high flows (freshet) and low flows. The Table 6.2 also includes the impact of wetlands on LC NBS and flows at Rapid Fryers station.

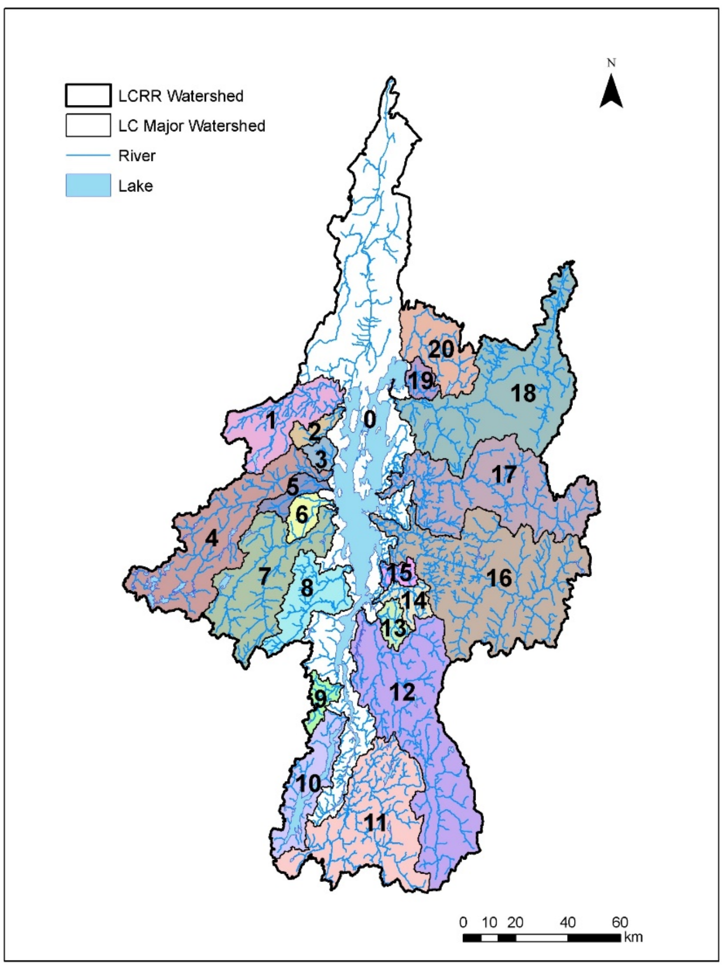

Figure 6.2 Major LC sub-watersheds (>100 km²).

Table 6.2 Impacts of existing wetlands on high flows and low flows of the 20 LC sub-watersheds, LC NBS and RR flows at Rapid Fryers.

#	WATERSHED	DRAINAGE (km²)	WETLANDS (%)	W DRAINAGE (%)	HIGH FLOW (%)	LOW FLOW (%)
1	Great Chazy	778	13.8%	47.6%	-40%	20%
2	Little Chazy	143	14.2%	50.9%	-40%	19%
3	Dead Creek	114	24.0%	55.3%	-54%	288%
4	Saranac	1579	11.6%	48.2%	-30%	10%
5	Salmon	177	8.3%	51.0%	-34%	26%
6	Little Ausable	188	6.7%	50.2%	-36%	22%
7	Ausable	1329	5.7%	37.6%	-18%	44%
8	Bouquet	621	6.1%	41.1%	-22%	101%
9	Putnam Creek	158	7.5%	51.4%	-36%	80%
10	La Chute	678	3.7%	25.7%	-10%	0.4%
11	Poultney	1778	6.8%	43.6%	-30%	64%
12	Otter Creek	2446	9.1%	39.3%	-20%	6.8%
13	Little Otter Creek	153	11.8%	51.9%	-59%	143%
14	Lewis Creek	203	7.8%	39.6%	-30%	56%
15	LaPlatte	118	6.7%	36.5%	-37%	339%
16	Winooski	2756	2.9%	23.9%	-9%	30%
17	Lamoille	1866	5.0%	37.9%	-18%	15%
18	Missisquoi	2212	7.0%	40.1%	-21%	21%
19	De La Roche	144	10.7%	43.0%	-34%	70%
20	Aux Brochets	664	8.5%	32.8%	-30%	37%
	LC NBS	**21254**	**7.3%**	**36.5%**	**-25%**	**17%**
	RR (Fryers)	**22055**	**7.3%**	**35.8%**	**-10%**	**0.4%**

Generally speaking, for small sub-watersheds with a high percentage of the watershed drained by wetlands, we observed a significant impact on 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 and low flow amplification. It is also important to add that a large amplification of low flows is often induced by the relative magnitude of low flows. Overall, the current distribution of wetlands reduces high flows by 25% and increase low flows by 17%. Downstream the damping effect of LC, wetlands still have a lingering effect and thus can reduce high flows by 10% on the Richelieu River at Fryers, while increasing low flows only by 0.4%. These results clearly illustrate the flow regulation services of the current distribution of wetlands in the LCRR watershed.

7 Wetlands construction/restoration scenarios

Based on readily available spatial data, we have designed a first-hand approach to design wetlands construction/restoration scenarios. At this stage of the study 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 on Figure 7.1).
2. Using the flow matrix, identification of the converging tiles towards the pit. Those 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 7.1) 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.

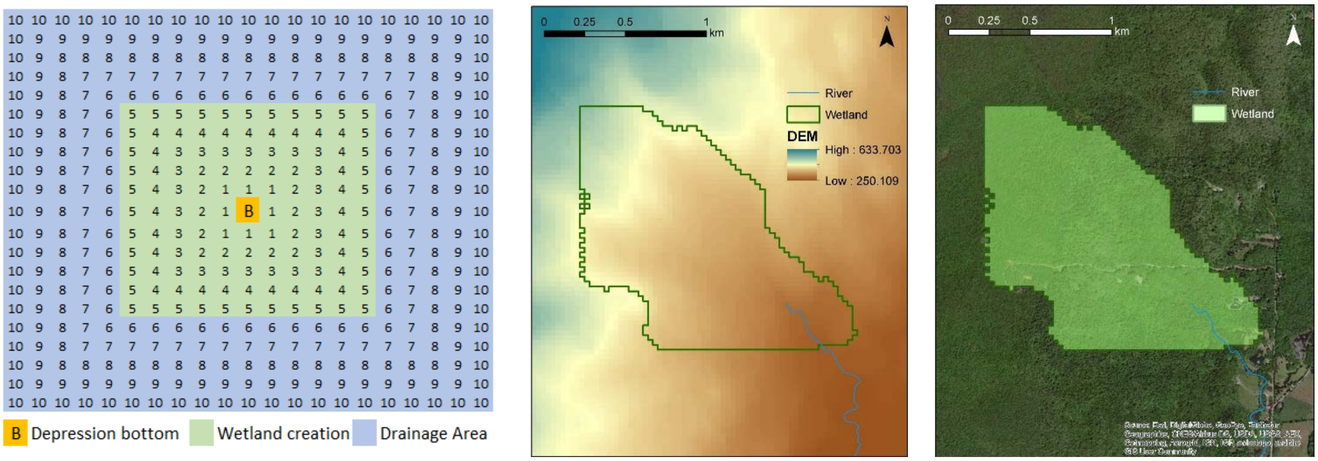

Figure 7.1 Development of a wetland scenario using a DEM and a few design criteria (e.g., wetland area or number of tiles converging towards the deepest tile and drainage area or minimum number tiles converging towards the wetland area).

Using this approach, we built a first conservative wetland construction/restoration scenario and evaluated the associated added value. This first scenario considered the addition of 76 km² of wetlands regardless of the sub-watershed. The simulation procedure is identical to the one described for the evaluation of the flow regulation services provided by wetlands (see Chapter 6).

A new hydrological simulation for the 1950-2013 can be performed using the newly created wetlands scenarios. Then the average gains refer to a comparison between the average high flows attenuation and average low flows amplification for the construction/restoration scenario and current wetlands within the LCRR watershed.

Table 7.1 introduces the results of this first wetland scenario in terms of gains in high flow attenuation and low flow amplification compared to the current status of wetlands in the LCRR watershed.

Table 7.1 The hydrological benefits of increasing the surface area of wetlands in the LC sub-watersheds in terms of reducing peak flows; LC NBS and RR flows at Fryers.

#	WATERSHED	DRAINAGE (km²)	WETLANDS		W DRAINAGE		HIGH FLOW		LOW FLOW	
			(%)	GAIN (%)	(%)	GAIN (%)	(%)	GAIN (%)	(%)	GAIN (%)
1	Great Chazy	778	13.8%	0.0%	47.7%	0.1%	-39.8%	-0.2%	19.8%	0.0%
2	Little Chazy	143	14.4%	0.2%	51.9%	1.1%	-41.3%	-1.1%	19.4%	0.0%
3	Dead Creek	114	24.0%	0.0%	55.3%	0.0%	-54.1%	0.0%	288.3%	0.0%
4	Saranac	1579	11.7%	0.1%	48.3%	0.1%	-30.4%	-0.2%	9.7%	0.0%
5	Salmon	177	8.3%	0.0%	51.1%	0.0%	-34.0%	0.0%	25.8%	0.0%
6	Little Ausable	188	6.7%	0.1%	50.9%	0.6%	-36.3%	-0.5%	22.3%	0.6%
7	Ausable	1329	6.1%	0.4%	38.3%	0.7%	-19.2%	-1.4%	45.3%	1.1%
8	Bouquet	621	6.2%	0.2%	41.4%	0.3%	-22.4%	-0.6%	100.8%	0.0%
9	Putnam Creek	158	7.5%	0.0%	51.4%	0.0%	-36.2%	-0.2%	79.8%	0.0%
10	La Chute	678	4.3%	0.6%	26.6%	0.8%	-12.1%	-2.4%	0.4%	0.0%
11	Poultney	1778	7.0%	0.2%	43.9%	0.3%	-30.5%	-0.6%	65.5%	1.2%
12	Otter Creek	2446	9.8%	0.6%	40.8%	1.5%	-21.8%	-1.3%	6.9%	0.1%
13	Little Otter Creek	153	11.8%	0.0%	51.9%	0.0%	-59.0%	-0.1%	143.3%	0.0%
14	Lewis Creek	203	7.8%	0.0%	39.8%	0.1%	-30.4%	-0.1%	55.6%	0.1%
15	LaPlatte	118	6.7%	0.0%	36.5%	0.0%	-37.1%	0.0%	339.5%	0.6%
16	Winooski	2756	3.3%	0.5%	25.3%	1.4%	-10.5%	-1.5%	31.8%	1.6%
17	Lamoille	1866	5.2%	0.2%	38.5%	0.6%	-18.3%	-0.7%	15.1%	0.5%
18	Missisquoi	2212	7.9%	0.9%	41.5%	1.4%	-23.5%	-2.4%	21.8%	1.3%
19	De La Roche	144	10.8%	0.1%	43.4%	0.4%	-34.7%	-0.4%	70.5%	0.3%
20	Aux Brochets	664	8.8%	0.3%	34.6%	1.9%	-30.7%	-0.8%	41.0%	4.4%
	LC NBS	**21254**	**7.6%**	**0.3%**	**37.2%**	**0.8%**	**-25.5%**	**-0.8%**	**17.5%**	**0.5%**
	RR (Fryers)	**22055**	**7.7%**	**0.3%**	**36.6%**	**0.8%**	**-10.3%**	**-0.5%**	**0.4%**	**0.0%**

Table 7.1 demonstrates that the addition of 76 km^2 of wetlands can lead to an increase in flow regulation services even with the addition of a modest area. Sub-watersheds where wetlands provided substantial services had the highest gains in high flow attenuation and low flow amplification. From a cumulative perspective, adding 76 km² of wetlands had a marginal effect on both LC NBS and RR flows at Fryers.

This first demonstration encourages the investigation of other wetland scenarios involving larger increase in surface area of wetlands and these will be assessed in the coming months.

8 Water storage scenarios on farmland

At this stage of the project, this task of constructing and assessing the use of riparian agricultural land for temporary water storage is at a starting point and still under development.

9 Learning from the 2011 flood

With a simplistic educated approach, we can attempt to use the 2011 flood to come up with a few wetlands or flooded farmland scenarios. Based on flow measurements at the Fryers station 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 surface area of additional wetlands farmland to hold up 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 8.1 provides an illustration of the simplified representation of the 2011 flows at the Fryers station from April 1st to July 3rd.

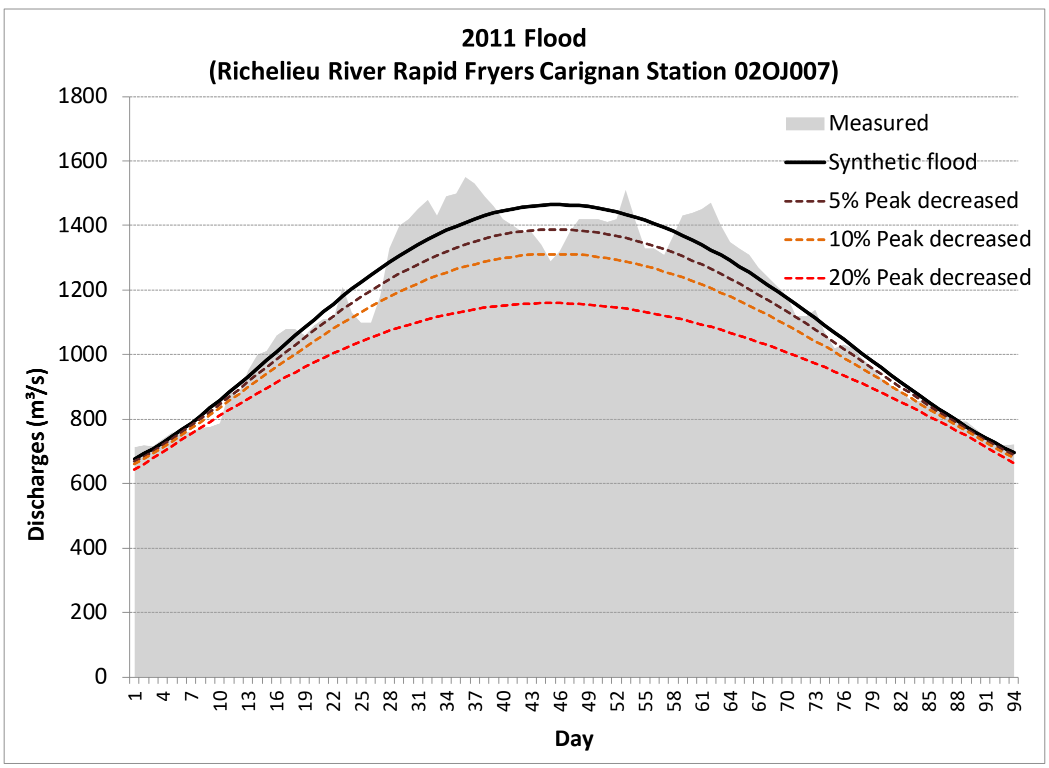

Figure 9.1 Simplified representations of the 2011 flood with a synthetic flood and ensuing shape of the flood given 5%, 10% and 20% reductions of the 2011 peak flow at the Fryers station from April 1st to July 3rd.

As mentioned, the peak flow reductions can be quantified in terms of volumes of water that could be stored in wetlands or over farmland as introduced in Table 9.1.

Table 9.1 Estimation of additional wetlands (area and % of increased compared to existing wetlands) or flooded farmland (in terms of % of existing farmland) required to reduce the 2011 peak flow of the RR at Fryers assuming the additional surface areas would either store 50 cm or 10 cm of water.

50-cm water height	Wetlands	Increased (%)		Farmland Flooding (%)	
Peak reduction scenario	(km²)	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	(km²)	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 an example reducing the 2011 peak flow at Fryers by 5% would require an additional 632 km² 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 Fryers watershed or by 41% wetlands in the LC watersheds. 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 Fryers station or 79% of the existing farmland of the LC watershed.

Table 8.1 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 quickly become unrealistic with a water holding capacity of 10 cm.

The next task will be to validate such scenarios using HYDROTEL and the wetland construction/restoration approach introduced in Chapter 7 and a flooding farmland scenario procedure to be developed. Moreover, combined wetland/farmland scenarios could be defined and evaluated.

10 Lessons learned and key messages

At this stage of the study some key element can outpointed.

1. The hydrologic modelling platform PHYSITEL/HYDROTEL is useful to assess flow regulation services provided by wetlands.

2. Existing wetlands play a key role in attenuating spring freshets and flooding and also increased low flows in specific LCRR sub-watersheds.

3. Construction of watershed storage scenarios (wetlands and flooding farmland) is challenging, but coming along.

4. Increasing watershed storage to reduce flood risk is a worthy and valuable investigation.

5. Wetlands construction/restoration or flooding farmland (riparian agricultural land) would require extensive surface area requirements; raising feasibility and acceptability issues.

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