



**McGill University**

**Department of Bioresource Engineering**

**Integrated Water Resources Management (IWRM) Program**

**BREE 631: IWRM INTERNSHIP PROJECT**

**Hydrological Analysis of the Historical May 2017 Flooding Event in Montreal and  
Surrounding Areas**

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## Table of Contents

1.0 Introduction .....	6
2.0 Overview of River Basins .....	9
2.1 Ottawa River Basin .....	9
2.1.1 General Characteristics .....	9
2.1.2 Water Use.....	11
2.1.3 Climate.....	11
2.1.4 Flooding in the Basin .....	12
2.2 Lake Ontario - St Lawrence River Basin .....	13
2.2.1 General Characteristics .....	13
2.2.2 Water Use.....	14
2.2.3 Climate.....	14
2.2.4 Flooding in the Basin .....	15
3.0 Plans, Boards and Acts for Flood Prevention .....	16
3.1 Ottawa River Regulation and Planning Board .....	17
4.0 Data Collection and Methods.....	18
4.1 Flood Frequency Analysis .....	20
4.1.1 Statistical Return Period.....	21
5.0 Hydrological Analysis .....	25
5.1 Warm and Wet Winter Season.....	25
5.2 Historical Recorded Water Levels .....	28
6.0 Conclusions.....	34
References .....	35

## List of Tables

Table 1- Principle Reservoirs in the Ottawa River .....	10
Table 2 - Corresponding F Limit levels for Lac St Louis corresponding to Lake Ontario Levels for limiting lower St Lawrence flooding damages. (International Joint Commission 2014) .....	17
Table 3- M Limit – minimum limit flows to balance low levels of Lake Ontario and Lake St. Louis primarily for Seaway navigation interest (International Joint Commission 2014).....	17
Table 4 - Hydro climatological stations used for data collection and analysis.....	19
Table 5 – Annual Precipitation for Weather Station at Rigaud.....	33

## List of Figures

Figure 1- Map Showing the St Lawrence Hydrographic System and Drainage Basins. (Source: Environment Canada, 2017) .....	7
Figure 2- Map of the Lake Ontario - St Lawrence River Basin (The National Academies Press 2017).....	8
Figure 3- Map Showing the direction of River Flows surrounding Montreal (Wikipedia, 2017).....	9
Figure 4 - Map of Ottawa River Basin Showing the 13 Main Reservoirs (ORRPB 2017).....	11
Figure 5- Mean monthly air temperature, precipitation and runoff for the Ottawa River Basin (James H. Thorp 2005).....	12
Figure 6- Graph representing peak flows of the Ottawa River (Source: Ottawa River Heritage Designation Committee, 2005) .....	13
Figure 7- Mean monthly air temperature, precipitation and runoff for the St Lawrence River basin (James H. Thorp 2005).....	15
Figure 8– Sketch Illustrating the Hydrology of Lake Ontario. (Source: IJC, 2017) .....	16
Figure 9 – Map showing the location of Gauging stations chosen for analysis. (Map created by J. Permansingh using Google Earth Pro image, August 2017) .....	19
Figure 10 - Flood frequency curve for gauging station at Lac St Louis (Pointe Claire) .....	23
Figure 11 - Flood frequency curve for gauging station at Pointe Fortune (Carillon).....	23
Figure 12 - Flood frequency curve for gauging station at Lac de Deux Montagnes .....	24

Figure 13 – Flood frequency curve for gauging station at St Anne de Bellevue.....	24
Figure 14 – Showing daily variation in Temperature for weather Station, Sainte Anne de Bellevue 1.....	25
Figure 15 – Showing daily variation in Temperature for weather Station, Rigaud.....	26
Figure 16 - Map Showing Total Precipitation Accumulation April 4 – 10, 2017 (Environment Canada 2017) .....	27
Figure 17 – Comparison of Average daily 2017 precipitation compared to the daily historical maximums for Sainte Anne de Bellevue .....	27
Figure 18 – Comparison of Average daily 2017 precipitation compared to the daily historical maximums for Rigaud .....	28
Figure 19 – Flood Hydrograph for Lac St Louis at Pointe Claire (IJC 2017).....	29
Figure 22 – Flood Hydrograph of Lac de Deux Montagnes (Jan. 1 to July 31, 2017).....	31
Figure 24 - Flood Hydrograph for Pointe Claire (April 1 to May 31, 2017).....	32

## Abstract

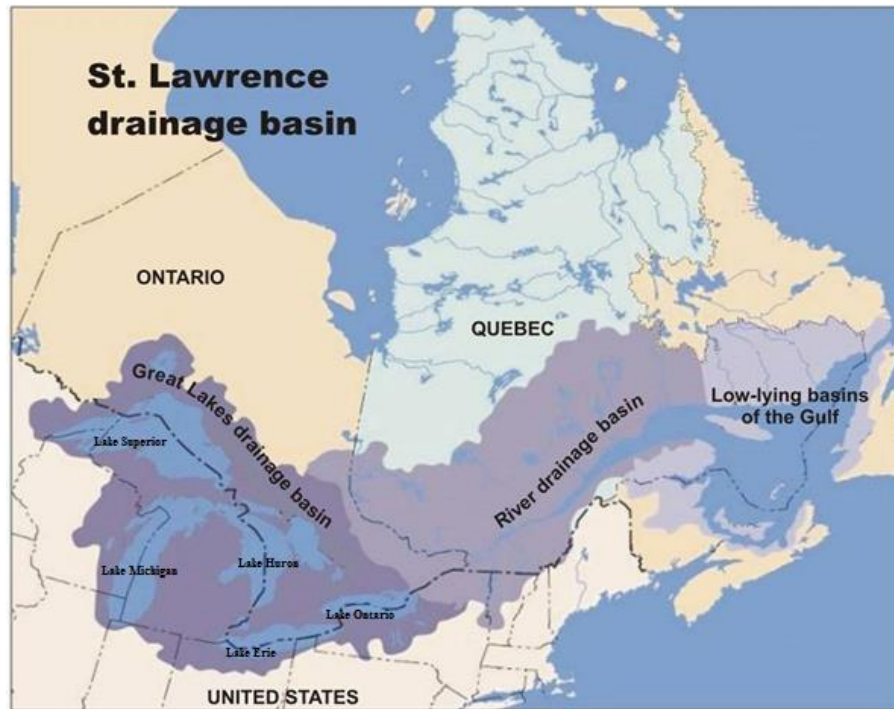
*Records show that the last flooding event in Montreal and surrounding areas of comparable nature to the May 2017 flooding event was experienced in 1976. Montreal is located within the St Lawrence River which links the Atlantic Ocean with the Great Lakes and is one of the world's most important commercial waterways. This immense basin has a population of over 30 million Americans and 15 million Canadians. It runs 3,058 Km from its farthest headwater (North River, Minnesota) and 1,197 Km from the outflow at Lake Ontario. The St Lawrence hydrographic system is one of the largest in the world and the third largest in North America after the Mississippi and McKenzie Rivers. It has a surface area of more than 1.6 million Km<sup>2</sup> and drains more than 25% of the earth's fresh water reserves. The Ottawa River system experiences low flows in the fall and a sudden increase in flows during the spring snowmelt period with floods in April to early May. Warm temperatures coupled with precipitation events created a freezing and thaw effect within the St Lawrence and Ottawa River Basins since January 2017 which then transitioned into a wet spring with above average rainfall in the river system. This resulted in historical maximum flows at the outlet of the Ottawa Rivers, Lake Ontario and historical maximum recorded levels at Lac de Deux Montagnes which influences the flows through Riviere des Prairies on the northern shore of Montreal and also the levels in Lac St Louis on the west island shoreline of Montreal. With maximum water levels experienced, and to prevent further increase in water levels at Lac St Louis, causing further damage, the International Lake Ontario – St Lawrence Board reduced outflows from Lake Ontario in accordance with Plan 2014. Plan 2014 was implemented to balance the impacts of flooding both upstream and downstream of the river system by limiting the effects of flooding around the Lac St Louis area. Flood hydrographs for the years 2006, 2011 and 2012 (includes wet and dry years) were compared and there was no major difference in the flood peaks recorded at the gauging station for Lac de Deux Montagnes which concludes that the flows were*

*perfectly controlled in the Ottawa River system in the past. The study further concluded that apart from the wet and warm winter that was experienced which contributed directly to the flooding event in Montreal, the inflow forecasting model used by the Ottawa River Regulation and Planning Board (ORRPB) as a guide to the decision-making process to assists in the release of flows from each control facility and to maintain flood control did not work for the wet and warm winter which rapidly transitioned into a wet spring, as record historical flows were recorded at the outflow of the Ottawa River which directly influenced flooding of Montreal and surrounding areas.*

## **1.0 Introduction**

Extreme events such as flooding is not a new phenomenon worldwide. Records show that the last flooding event in Montreal and surrounding areas of comparable nature to the May 2017 flooding event was experienced in 1976. Anthropogenic changes in our river systems such as the construction of reservoirs, land development and improvement for human settlement, etc., have led to both positive and negative outcomes as it relates to water resources and flood management in our river systems.

The St Lawrence River links the Atlantic Ocean with the Great Lakes and is one of the world's most important commercial waterways. This immense basin has a population of over 30 million Americans and 15 million Canadians (Environment Canada 2017). It runs 3,058 Km from its farthest headwater (North River, Minnesota) and 1,197 Km from the outflow at Lake Ontario. The St Lawrence hydrographic system is one of the largest in the world and the third largest in North America after the Mississippi and McKenzie Rivers. It has a surface area of more than 1.6 million Km<sup>2</sup> and drains more than 25% of the earth's fresh water reserves (Environment Canada, 2017).



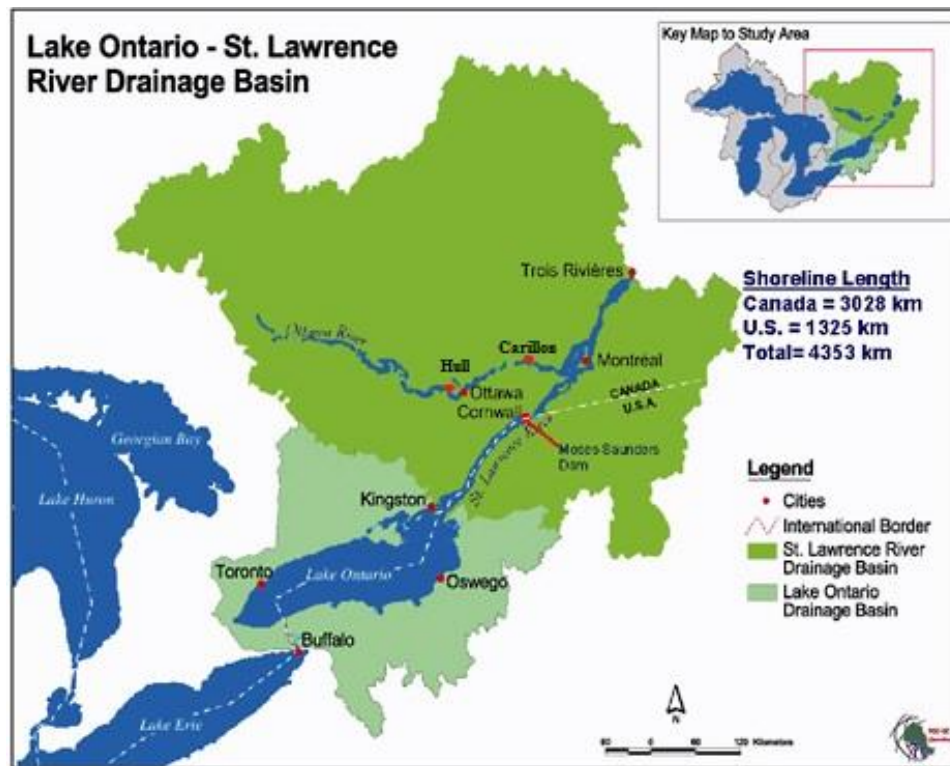
*Figure 1- Map Showing the St Lawrence Hydrographic System and Drainage Basins. (Source: Environment Canada, 2017)*

The entire basin has varying land use and cover, with 55% being forested, 20% cropland (with little or no irrigation), 22% urban, and 3% other types of land cover (Revenga 1998). This hydrographic system comprises of Lake Michigan, Lake Superior, Lake Huron, Lake Erie, Lake Ontario and the main stem of the St Lawrence River.

This study focuses on the analysis of the physical hydrology of the Lake Ontario - St Lawrence River Basin (LOSLR). This basin includes the lower Niagara River, Lake Ontario and the St. Lawrence River basin. International waters shared by the Lake Ontario St Lawrence River basin extends from the lower Niagara River downstream from the Niagara Falls, through Lake Ontario and the upper St Lawrence River to just downstream from the Moses Saunders Dam near the towns of Massena, New York and Cornwall, Ontario; from there the St Lawrence River flows through the Canadian province of Quebec near the cities of Montreal and Trois Rivieres, until it discharges into the Gulf of the St Lawrence (fig. 1). The LOSLR basin supplies drinking water for some 8.6 million people and supports a very complex aquatic, wetland and coastal eco-systems that are affected by water flow and fluctuations.

The St Lawrence River starts at the outflow of Lake Ontario and is the main drainage outlet for Lake Ontario. A difference of even a half of a meter in Lake Ontario water levels can aggravate

flooding, erosion, boating problems, wetland habitat and fish spawning habitat (The National Academies Press 2017). Water levels at Lac St Louis (fig. 3) is governed by the outflows from Lake Ontario through the Moses-Saunders dam (fig. 2) and if not properly managed can have severe and catastrophic end results for the island of Montréal and riparian areas along the St Lawrence River.



*Figure 2- Map of the Lake Ontario - St Lawrence River Basin (The National Academies Press 2017)*

Montreal is situated at the confluence of the Ottawa River with the St Lawrence and is also affected by flows from the Ottawa River. The Ottawa River at Carillon generates two flood peaks which has a direct effect on the water levels in Lac de Deux Montagnes, Lac St Louis and Riviere des Prairies which all shares a shoreline with Montreal (Fig 3).



*Figure 3- Map Showing the direction of River Flows surrounding Montreal (Base map sourced from Wikipedia, 2017)*

These river systems play an important role to the economies of both the United States and Canada therefore it is important to understand the physical hydrology as to better manage its water resources and minimize the effects of extreme events. This study as stated in the topic aims at understanding the physical hydrology of the May 2017 flooding in Montreal, through thorough analysis of readily available hydrological and climate data so that main reasons for the flooding event can be understood.

## **2.0 Overview of River Basins**

### **2.1 Ottawa River Basin**

#### **2.1.1 General Characteristics**

The Ottawa River has a length of more than 1,130 Km from its source east of the Dozois Reservoir to its confluence with St Lawrence River and for most of its length acts as the boundary between the provinces of Ontario and Quebec. It has a vertical descent of 365m which produces an average slope of 0.315 m/Km; 84m of this plunge occurs along a short 22.5 Km stretch between Lake Quinze-Simard and Lake Temiskaming whilst the remainder occurs gradually along the stretch of the River. This watershed has a total area of 146,300 Km<sup>2</sup> of which 65 percent represents Quebec's landmass and 35 percent being in Ontario.

Land use and land cover for this basin represents: 86% being forest, 10% surface waters, 2% urban, and 2% agriculture (Revenga 1998). The Ottawa River watershed has 30 storage reservoirs which has a holding capacity of more than 14 billion cubic meters of water. Table 1 shows the thirteen principle reservoirs with their respective holding capacities.

The mean annual discharge of the Ottawa River is 1942 m<sup>3</sup>/s with maximum historical flows as high as 8190 m<sup>3</sup>/s and minimum flows of 306 m<sup>3</sup>/s over the past Fifty-Two (52) years (1964 – 2016), (ORRPB 2017).

*Table 1- Principle Reservoirs in the Ottawa River*

<b>NO.</b>	<b>RIVER</b>	<b>RESERVOIR</b>	<b>CAPACITY*</b>
<b>1</b>	Outaouais	Dozois	1,863
<b>2</b>		Rapid VII	371
<b>3</b>		Quinze	1,308
<b>4</b>		Timiskaming	1,217
<b>5</b>		Des Joachims	229
<b>6</b>	Montreal	Lady Evelyn	308
<b>7</b>	Kipawa	Kipawa	673
<b>8</b>	Madawaska	Bark Lake	374
<b>9</b>	Gatineau	Cabonga	1,565
<b>10</b>		Baskatong	3,049
<b>11</b>	Lievre	Mitchinamecus	554
<b>12</b>		Kiamika	379
<b>13</b>		Poisson Blanc	625

\*Capacity measured in millions of cubic meters  
(Source: ORRPB 2017)



*Figure 4 - Map of Ottawa River Basin Showing the 13 Main Reservoirs (ORRPB 2017)*

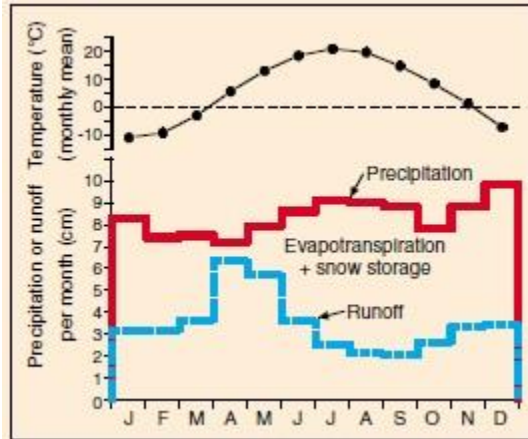
### **2.1.2 Water Use**

The Ottawa River in the early years was used mainly for navigational purposes, hence the first reservoirs were built in aid of augmenting low flows during dry years and to some level provide flood control measures, however with rapid urbanization in the 20<sup>th</sup> century and changes in need of the basin's population there has been a change in uses of the River (ORRPB 2017). Presently the greatest use of water in this river basin is for hydroelectric power generation, domestic water supply and effluent dilution, recreational boating and to a lesser extent log driving. According to the Ottawa River Regulation Planning Board there are 43 hydroelectric generating stations in the Ottawa River Basin with a combined capacity of some 3,500 Megawatts representing an electrical value of about \$1 million per day which is very important to the economies of both Quebec and Ontario.

### **2.1.3 Climate**

The climate within this basin is like many parts of the Canadian Shield and St Lawrence lowlands and can be classified as humid continental with mesoscale local effects caused by the Great Lakes and Hudson Bay (Farvolden R.N. 1988).

The basin experiences an average total precipitation of 880 mm of which 445mm leaves as runoff (Ontario Water Resources Commission and Quebec Water Board 1971).



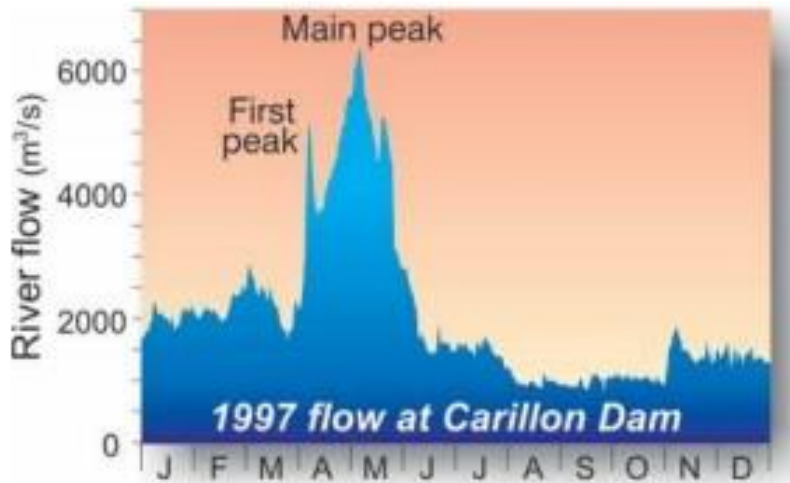
*Figure 5- Mean monthly air temperature, precipitation and runoff for the Ottawa River Basin (James H. Thorp 2005).*

Figure 2 illustrates that there is an increase in surface runoff for the months of April and May which represent the peak of the spring snow melt period where the soil is saturated (Ottawa River Heritage Designation Committee 2005). As precipitation rates increase for the summer months there is a decrease in surface runoff due to increased potential abstraction (soil moisture retention) caused by increased evapotranspiration and reservoir storage.

#### **2.1.4 Flooding in the Basin**

The Ottawa River system experiences the same general pattern of flow as shown for the surface runoff in figure 5, with low flows in the fall and a sudden increase in flows during the spring snowmelt period with floods in April to early May (Ottawa River Heritage Designation Committee 2005).

Due to the basin's size, shape and topography and highly varied meteorological conditions, the basin produces two distinct flood peaks, about three weeks apart (fig. 6). At Carillon, the first peak originates from unregulated flows from its southern tributaries and the second peak from a combination of high flows from tributaries of the north shore together with flows from headwater areas, and is partially regulated (Ottawa River Heritage Designation Committee 2005). It is further stated by the Ottawa River Designation Committee 2005, that the second peak which is usually the larger peak can be detrimental with a heavy snowpack, a late thaw, above normal rains, or a combination of these abnormalities causing flooding of downstream areas from Carillon such as Rigaud, Laval and Montreal (fig. 3).



*Figure 6- Graph representing peak flows of the Ottawa River (Source: Ottawa River Heritage Designation Committee, 2005)*

## **2.2 Lake Ontario - St Lawrence River Basin**

### **2.2.1 General Characteristics**

From a topographic perspective, the St Lawrence-Great Lakes River system is relatively flat in the western part but elevation levels rise to nearly 2000m in the mountainous eastern half of the basin (James H. Thorp 2005). The Lake Ontario - St Lawrence River basin is shared by the USA and Canada and drains the world's largest freshwater lake system, which includes the lower Niagara River, Lake Ontario and the St. Lawrence River basin (The National Academies Press 2017). International waters shared by the lower Great Lakes extends from the lower Niagara River downstream from the Niagara Falls, through Lake Ontario and the upper St Lawrence River to just downstream from the Moses Saunders Dam near the towns of Massena, New York and Cornwall, Ontario; from there the St Lawrence River flows through the Canadian province of Quebec near the cities of Montreal and Trois Rivières, until it discharges into the Gulf of the St Lawrence (fig. 2).

Lake Ontario has the smallest surface area of all the Great Lakes (18,960 km<sup>2</sup>) and has a drainage area of 64,030 Km<sup>2</sup> (James H. Thorp 2005). The St Lawrence main stem starts at the outflow of Lake Ontario and serves as its the main drainage outlet.

The St. Lawrence River has mean annual discharge of 12,101 m<sup>3</sup>/s (excluding Saguenay) at Quebec City and from the outlet at Lake Ontario to the end of the lower estuary the river drops 184m, with an average slope of 0.14 m/Km (Revenga 1998).

### **2.2.2 Water Use**

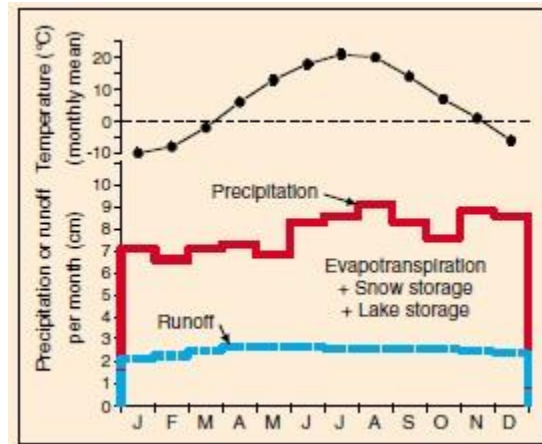
The LOSLR basin supplies drinking water for some 8.6 million people and supports a very complex aquatic, wetland and coastal eco-systems that are affected by water flow and fluctuations. Hydropower production at the Moses-Saunders dam averages at 13 million megawatt hours per year (The National Academies Press 2017). This river basin also serves as an important navigation route for global and regional maritime shipping from the Port of Montreal through the St Lawrence seaway.

### **2.2.3 Climate**

The St. Lawrence – Great Lakes river system stretches climatically from the inland climatic zone at its western edge to the oceanic edge in its eastern zone. This temperate region is classified as having mild humid summers to cold snowy winters (James H. Thorp 2005).

The Great Lakes and the Atlantic Ocean greatly affect precipitation patterns across the basin with precipitation varying between 560mm to 1110mm depending on a sites location either upwind or downwind of a major lake, however half of the precipitation entering a Lake Ontario is lost to the atmosphere via evaporation and transpiration before it enters the St. Lawrence River (James H. Thorp 2005).

Within the St. Lawrence River system precipitation is spread evenly throughout the year (Figure 5.) with the Montreal area averaging 942mm of precipitation annually (snow converted to rain equivalence) and ranges between 66mm in February to 91mm in August. The historical mean air temperature is 6.8°C with average monthly values ranging from -10°C in January to 21°C in July (fig. 7).



*Figure 7- Mean monthly air temperature, precipitation and runoff for the St Lawrence River basin (James H. Thorp 2005).*

#### 2.2.4 Flooding in the Basin

Figure 6 illustrates that water levels on the lake and St Lawrence River are determined largely by natural factors such as precipitation, evaporation and runoff. The International Joint Commission (IJC) estimates that on average 80 percent of water flowing into Lake Ontario comes from Lake Erie over Niagara Falls; uncontrolled water from the Ottawa River also has a major influence on downstream water levels in the Montreal area.

Controlled outflow from Lake Ontario is regulated from the Moses-Saunders dam and can have a rapid effect on water levels in the St Lawrence River upstream and downstream of the dam, but have a gradual effect on Lake Ontario water levels (IJC 2017). Water levels at Lac St Louis is governed by the outflows from Lake Ontario and if not properly managed can have severe and catastrophic end results for the island of Montréal and riparian areas along the St Lawrence River. A difference of even a half of a meter in Lake Ontario water levels can aggravate flooding, erosion, boating problems, wetland habitat and fish spawning habitat (The National Academies Press 2017). Most flows within this river system upstream of the Montreal area are controlled.

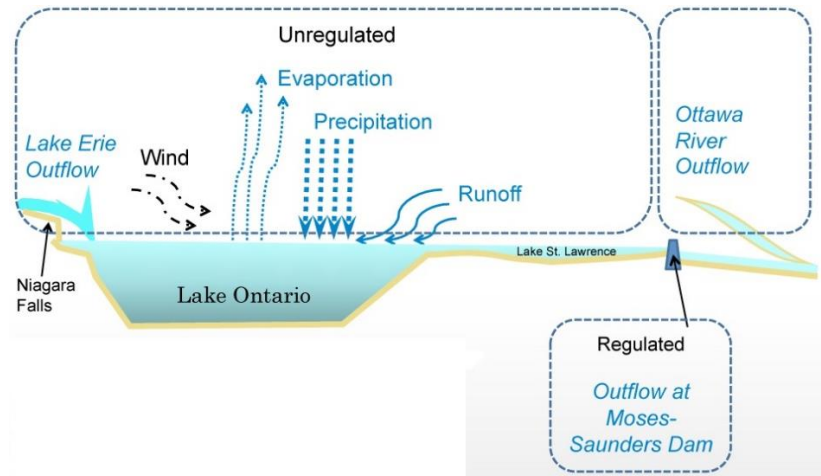


Figure 8– Sketch Illustrating the Hydrology of Lake Ontario. (Source: IJC, 2017)

### 3.0 Plans, Boards and Acts for Flood Prevention

The International Joint Commission (IJC) was created under the Boundary Waters Treaty of 1909 to help prevent disputes arising over the use of water along the USA - Canada boundaries. Its responsibilities are to approve projects that may change water levels on either side of the borders with the objective of protecting the interests of both countries (International St Lawrence River Board of Control 2017).

The International St. Lawrence River Board of Control was established by the IJC, mainly to ensure that outflows from Lake Ontario meet the requirements of the Commission's Orders of Approval.

Plan 1958 – D was implemented in 1963 by the IJC with the main objective of reducing the frequency of low water levels at the Montréal harbour by regulating the outflows from Lake Ontario (The International St Lawrence River Board of Control 1963).

The IJC on December 8, 2016 issued a supplementary order, replacing Plan 1958-D and adopting Plan 2014 as the new regulation plan that was effective as of January 7, 2017 (IJC 2017). This new plan prescribes a new set of rules that the board must follow in setting the outflows from Lake Ontario through the St Lawrence River at the Moses-Saunders hydro-electric dam at Cornwall, Ontario and Massena, New York.

Plan 2014 sets flows to balance the risk of flood damages, both on Lake Ontario and the St. Lawrence River downstream, by keeping the level of Lac St. Louis below and above given thresholds for a corresponding Lake Ontario level (IJC 2017). As the level of Lake Ontario rises,

the threshold level on Lake St. Louis also rises, allowing more water to be released from Lake Ontario (Tables 2 & 3).

*Table 2 - Corresponding F Limit levels for Lac St Louis corresponding to Lake Ontario Levels for limiting lower St Lawrence flooding damages. (International Joint Commission 2014)*

<b>Lake Ontario Level (m)</b>	<b>Lac St Louis Level @ Pointe Claire (m)</b>
<b>&lt;75.3</b>	22.10
<b>≥75.3 to ≤75.37</b>	22.20
<b>≥75.37 to ≤75.5</b>	22.33
<b>≥75.5 to ≤75.6</b>	22.40
<b>≥75.6</b>	22.48

*Table 3- M Limit – minimum limit flows to balance low levels of Lake Ontario and Lake St. Louis primarily for Seaway navigation interest (International Joint Commission 2014).*

<b>Lake Ontario Level (m)</b>	<b>Lac St Louis Level @ Pointe Claire (m)</b>
<b>&lt;74.2</b>	20.64
<b>≥74.1 to ≤74.2</b>	20.54
<b>≥74.0 to ≤74.2</b>	20.43
<b>≥73.6 to ≤74.0</b>	20.39
<b>≥73.6</b>	20.39 or less

### **3.1 Ottawa River Regulation and Planning Board**

Established in 1983 by the governments of Canada, Quebec, and Ontario the goal of the Ottawa River Regulation Planning Board (ORRPB) is to ensure the integrated management of the principal reservoirs of the Ottawa River Basin. The main aim is to provide protection against flooding along

the Ottawa River and its tributaries, particularly in the Montreal Region, and at the same time maintain the interests of the various users particularly in hydro-electric energy production (ORRPB 2017).

During an approaching flood, strategies will be assessed and revised as necessary each day to minimize the flooding in the whole basin (ORRPB 2017). The board uses an inflow forecasting model that simulates the hydrology of the watershed as a guide to the decision-making process to assist the operators in the release of flows from each control facility to maintain flood control while having the least effect on the various other uses in the basin. Results from this model is used to keep the public informed on flows and levels, and their expected variations.

#### **4.0 Data Collection and Methods**

A large part of the study consisted in performing a thorough search for historical available climate, water levels and flow data for gauging stations surrounding the Montreal area. To analyze the magnitude of the recent May 2017 flooding event in Montreal and surrounding areas these gauging stations were selected based on the most complete and long-duration hydrological series (table 4). Gauging stations at Pointe Fortune (Carillon), Lac de Deux Montagnes, Ste Anne de Bellevue and lac St Louis (fig.9) were chosen for river flows and level data with corresponding local meteorological stations within proximity of the gauging stations (table 4). Environment Canada online historical database had 2 meteorological stations for the Ste Anne de Bellevue area, Ste Anne de Bellevue 1 was chosen for analysis since there was available daily climate data for the period 1994 to 2017; the other station named Ste Anne de Bellevue had available weather data for period 1969 to 1992 which was not necessary for this study. The hydrological variables selected for analysis in the study includes, annual maximum water levels and flows, annual mean levels and flows, monthly mean levels and flows and daily maximum levels and flows. Climatic variables selected include temperature and precipitation for different time series.

Data obtained for this study were obtained from Environment Canada online databank (Environment Canada 2017), Hydro Quebec and Quebec's Ministry of Environment online databank (Quebec Government 2017).

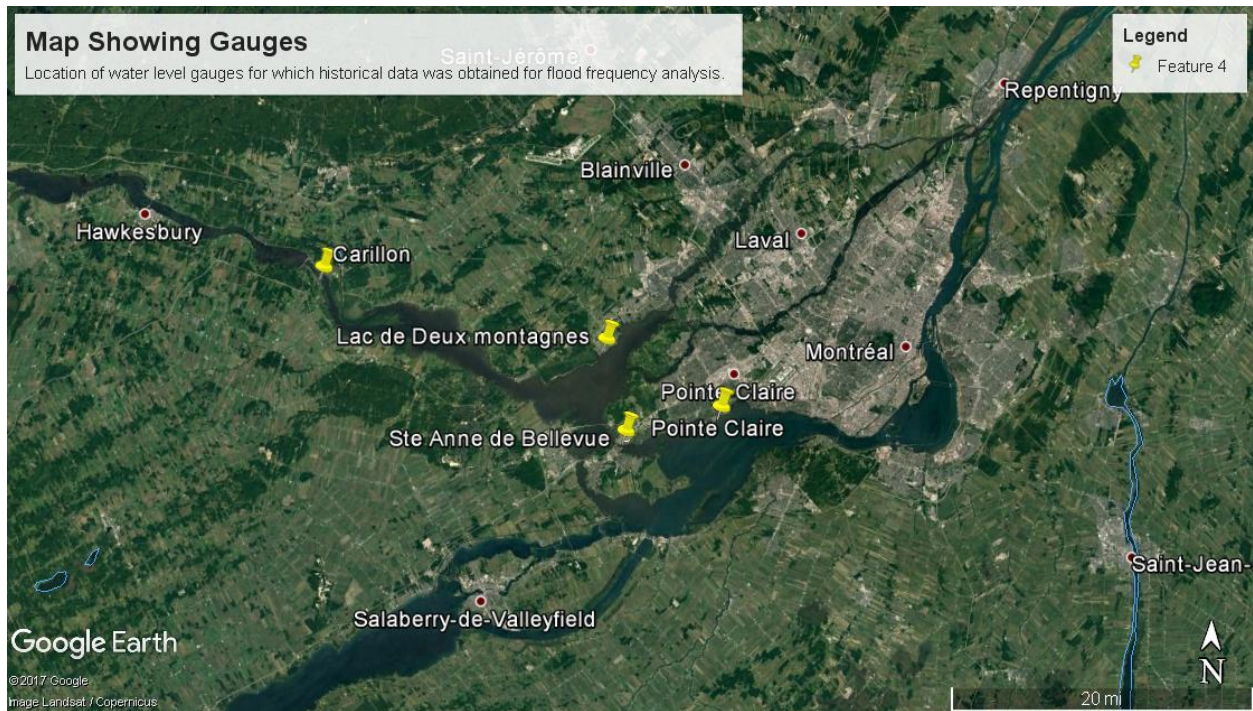


Figure 9 – Map showing the location of Gauging stations chosen for analysis. (Map created by J. Permarsingh using Google Earth Pro image, August 2017)

Table 4 - Hydro climatological stations used for data collection and analysis.

Meteorological Station	Number	Location	Elev. (m)	Temp . (°C)	Precip. (mm)	Data	Source
Ste Anne de Bellevue 1	702FHL 8	45.43°N — 73.93°W	39	1993 - 2017	1993 - 2017	Climate	Env. Canada
Rigaud	7016470	45.5°N – 74.37°W	46	1963 - 2017	1963 - 2017	Climate	Env. Canada
Montreal/Pierre Trudeau Intl	702S006	45.47°N — 73.74°W	32.1	2002 - 2017	2002 - 2017	Climate	Env. Canada

Ottawa CDA RCS	6105978	45.38°N — 75.72°W	79.2	2000 - 2017	2000 - 2017	Climate	Env. Canada
Gauging Station	Number	Location	Basin (Km <sup>2</sup> )	Period		Data	Source
Ste Anne de Bellevue	020A033	45.40°N — 73.95°W	N/a	1978 - 2017		Level	Env. Canada
Saint Louis (LAC) a Pointe - Claire	020A03 9	45.43°N — 73.82°W	N/a	1915-2017		Level	Env. Canada
Lac de Deux Montagnes	043108	45.49°N — 73.98°W	146,548	1986-2017		Level	Ministry of Env., Quebec
Carillon at Pointe Fortune	N/a	N/a	146,300	1974, 1976 & 2017		Flow	Hydro Quebec
Hull	02LA015	45.43°N — 75.71°W	N/a	1964 - 2017		Level	Env. Canada

#### 4.1 Flood Frequency Analysis

The general objective of the flood frequency analysis in this study is to interpret a past record of hydrologic event in terms of future probabilities of occurrence. The procedure involves fitting a theoretical distribution to a sample and making inferences about the underlying population. For analysis to be valid, data must satisfy certain statistical criteria such as randomness, homogeneity and stationarity.

To calculate the estimates of exceedance probabilities associated with historic observations, the Weibull plotting position formula is used as shown below:

$$p_{est} = \frac{r}{N + 1} \quad (1)$$

Where:

$p_{est}$  - Is the estimated probability of occurrence (multiplied by 100 gives the percentage probability)

$r$  - Is the rank given to a specific row in the data series. The highest discharge or water level has a rank of 1, the second highest 2 etc.

$N$  – Number of values in the series.

#### 4.1.1 Statistical Return Period

Assuming that  $X$  is a random variable which has a cumulative distribution function  $F_X(x)$ . The probability that  $X$  is less than equal to a given event  $x_p$  is given as:

$$F_X(x) = P(X \leq x_p) = p \quad (2)$$

The probability that this event will be exceeded is then equal to  $1-p$  and the percent exceedance is denoted as  $100(1-p)$ . For such an event  $x_p$ , the return period corresponding to this exceedance probability is denoted by  $T$ .

Here, 
$$T = 1/(1 - p) \quad (3)$$

Using this definition, the 100-year return period can be understood as an event with a probability of exceedance  $1-p = 0.01$  or a non-exceedance probability  $p=0.99$ . In other words, there is a 99% chance that this event will not be exceeded within a given year.

Using this concept of  $T$ , ' $T_p$  estimated' is calculated. ' $T_p$  estimated' represents the estimated distribution of the number of years of historical data used for the given station.

Now we will assume that the data follows a specific distribution and estimate the parameters of the distribution. In this study, the data is assumed to follow the 'Gumbel' or Extreme Value Type 1' distribution. The CDF of the Extreme Value Type I or Gumbel distribution is given as follows:

$$F_x(x) = \exp \left[ -\exp \left( -\frac{x-u}{\alpha} \right) \right] = p \quad (4)$$

Where  $x$  is the observed discharge data, and  $u$  and  $\alpha$  are the calculated parameters of the distribution. We will use this distribution to calculate the theoretical estimate of 'p'. To calculate 'p theoretical', we will need to calculate the value of  $(x-u)/\alpha$  using the equations given below where  $\mu$  and  $\alpha$ , are parameter estimates in terms of sample moments and are given by:

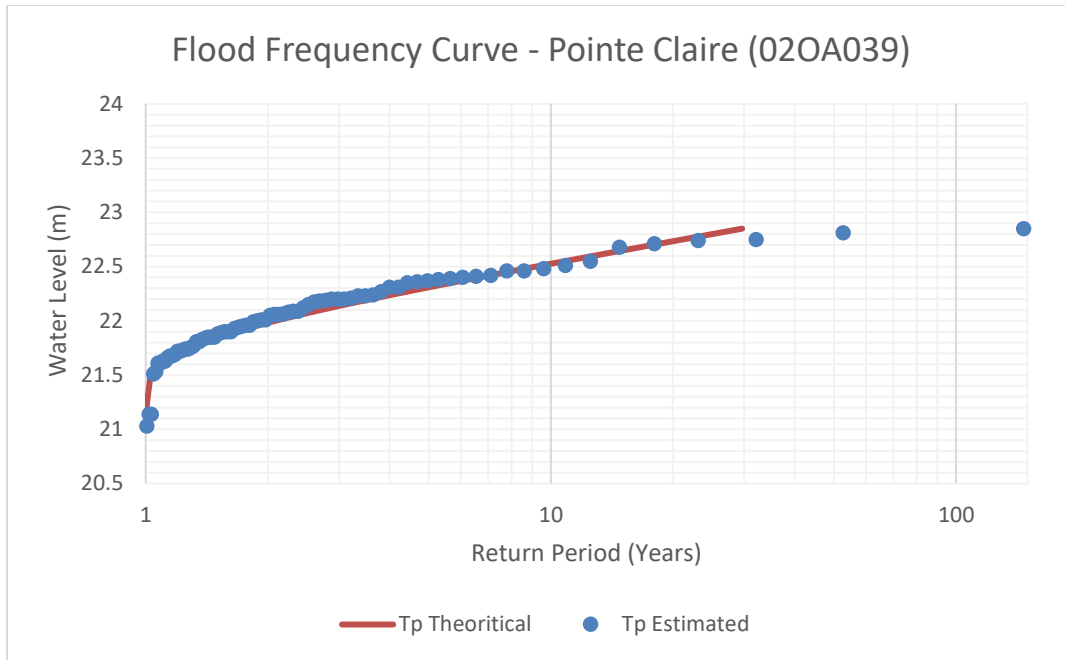
$$\bar{x} = \sum_{i=1}^n \frac{x_i}{n} \quad (5)$$

$$s_x^2 = \frac{1}{(n-1)} \sum_{i=1}^n (x_i - \bar{x})^2 \quad (6)$$

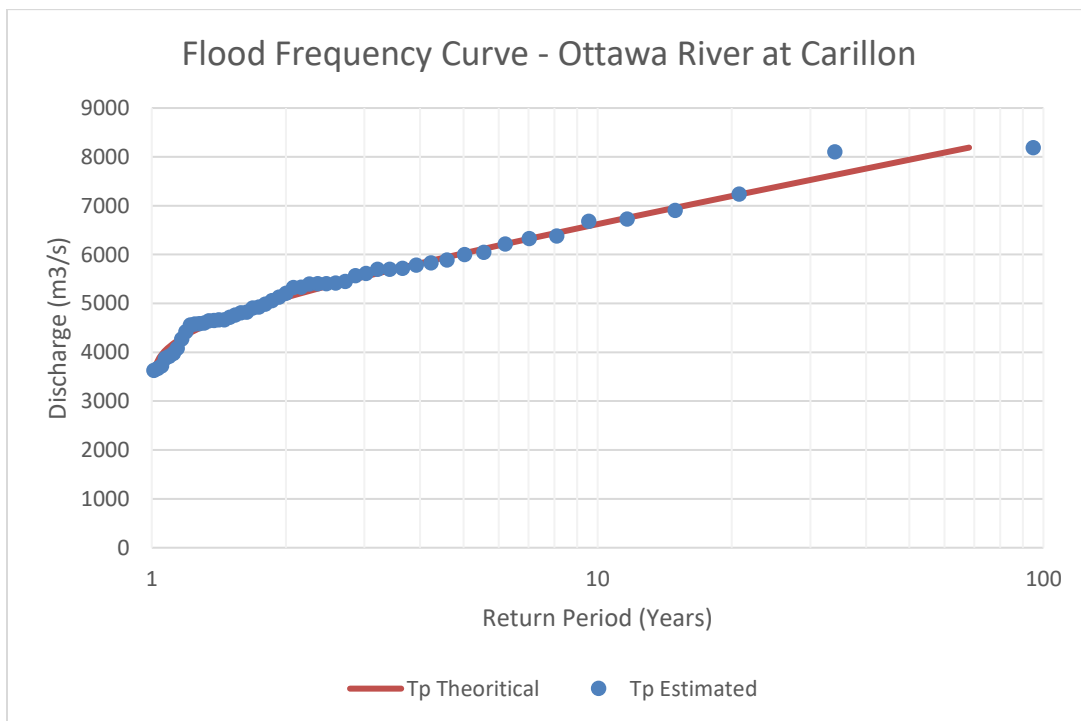
$$u = \bar{x} - 0.5772\alpha \quad (7)$$

$$\alpha = \frac{\sqrt{6}s_x}{\pi} \quad (8)$$

Figures 10, 11, 12 and 13 represents the flood frequency curves from which the flow and water level values corresponding to return periods of 5, 20, 50 and 100 years were obtained to analyze the magnitude of the flooding event.



*Figure 10 - Flood frequency curve for gauging station at Lac St Louis (Pointe Claire)*



*Figure 11 - Flood frequency curve for gauging station at Pointe Fortune (Carillon)*

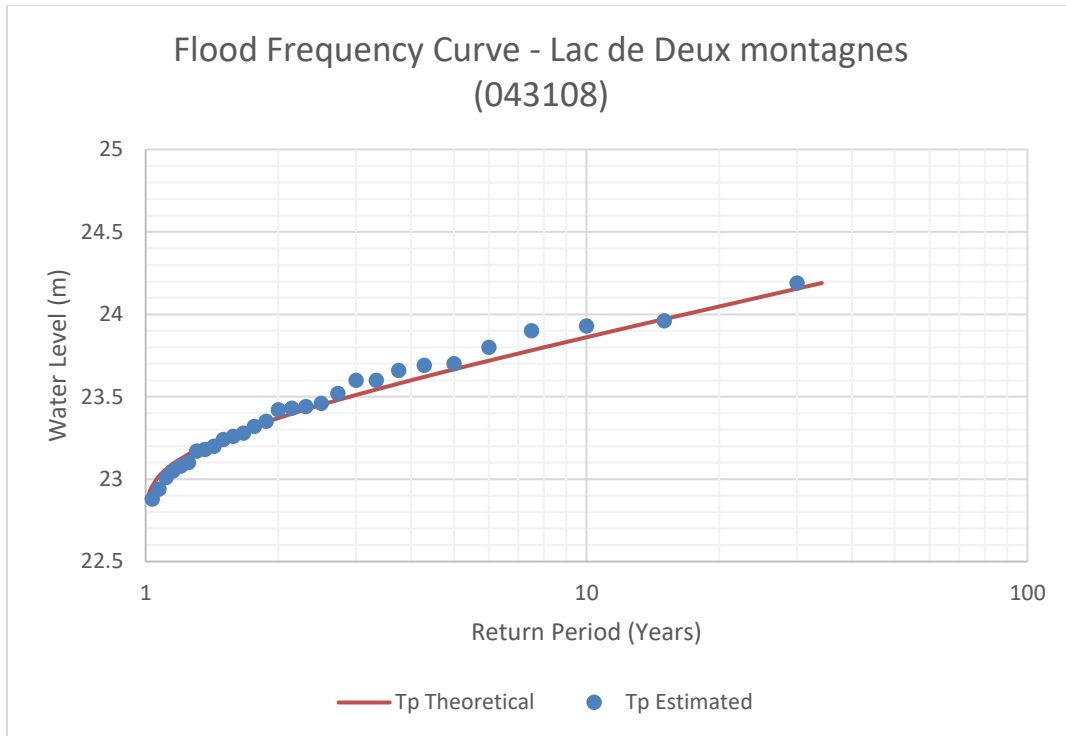


Figure 12 - Flood frequency curve for gauging station at Lac de Deux Montagnes

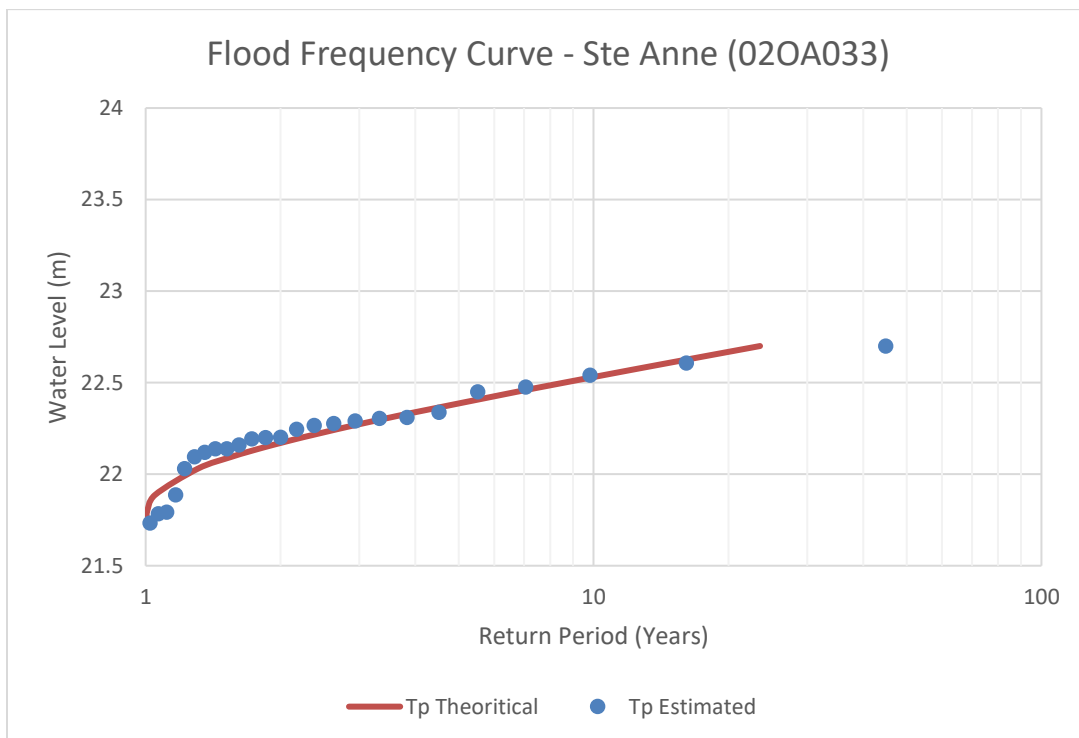


Figure 13 – Flood frequency curve for gauging station at St Anne de Bellevue

## 5.0 Hydrological Analysis

### 5.1 Warm and Wet Winter Season

It is regulatory that when ice starts to form at critical locations along the St. Lawrence River that outflows must be reduced temporarily as to ensure the formation of a stable ice cover (IJC 2017). This is done as to reduce the risk of the ice collapsing and moving with the flow of the water which can lead to ice jams causing immediate flooding upstream and subsequently reducing flows downstream.

Warm temperatures coupled with precipitation events created a freezing and thaw effect within the St Lawrence and Ottawa River Basins since January 2017. At Rigaud and Sainte Anne de Bellevue the temperatures rose above 0°C two times between the 11<sup>th</sup> January and the 23<sup>rd</sup> of January (fig. 14 & 15).

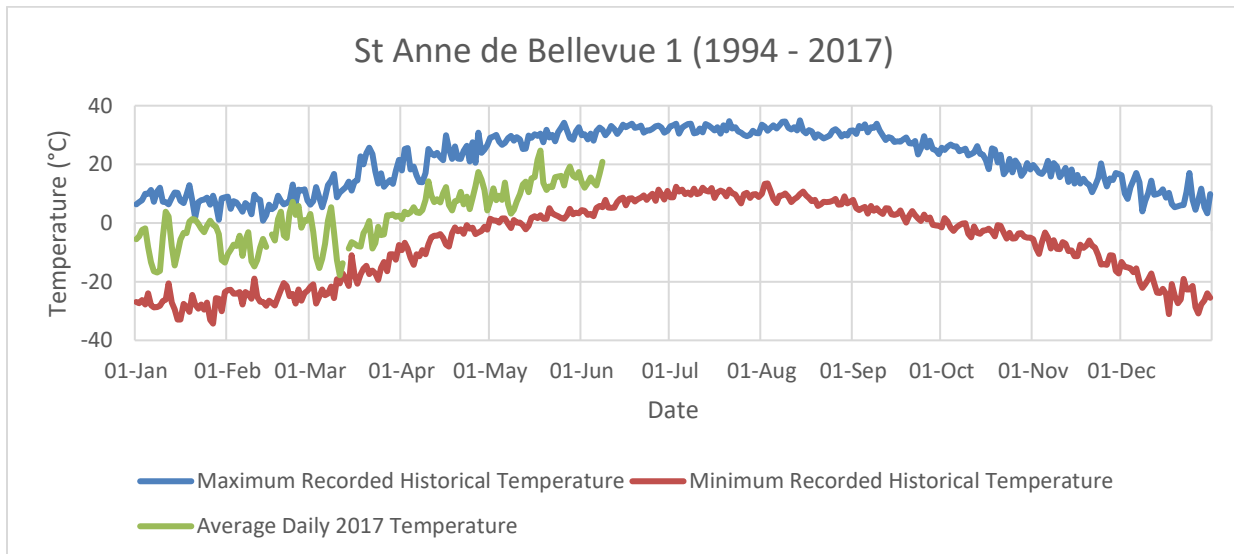
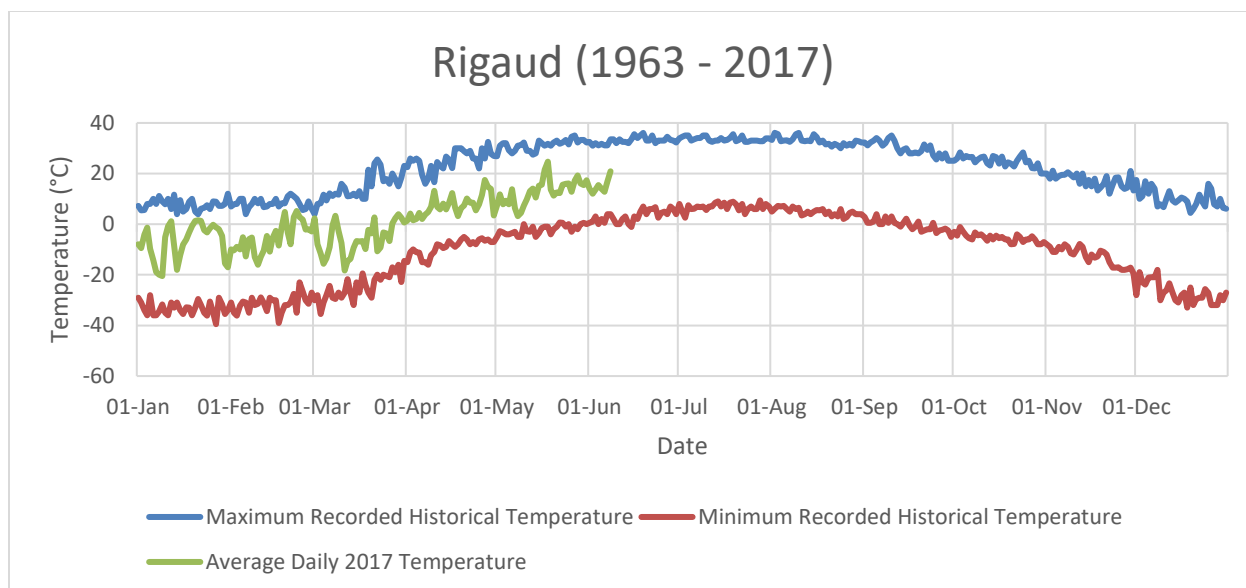


Figure 14 – Showing daily variation in Temperature for weather Station, Sainte Anne de Bellevue

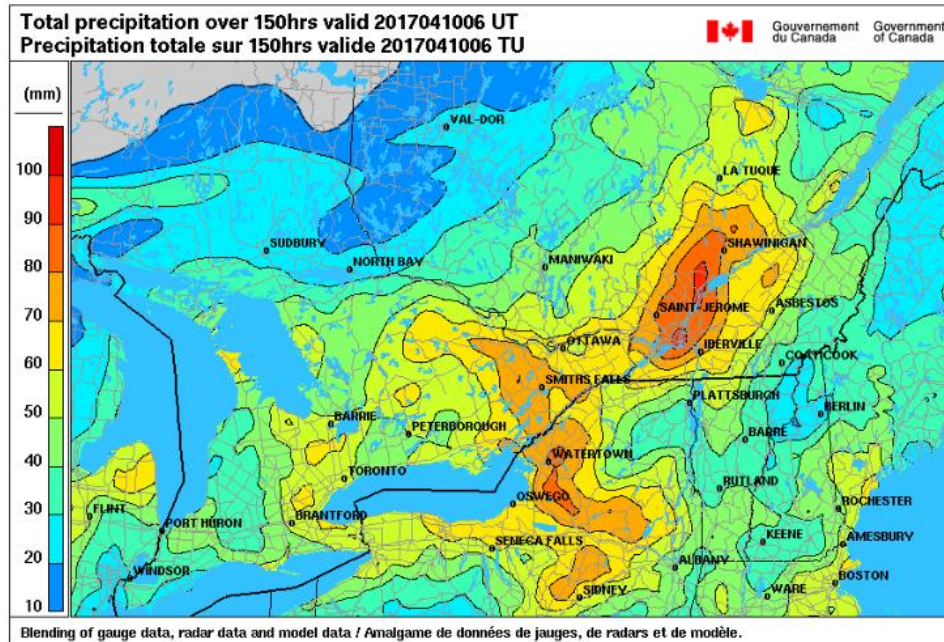


*Figure 15 – Showing daily variation in Temperature for weather Station, Rigaud.*

This warm winter weather continued in February with more days above freezing point compounded with snowfall. Since the temperatures were above 0°C for the days with almost maximum daily historical precipitation, the snowfall melted and made its way into the rivers and streams.

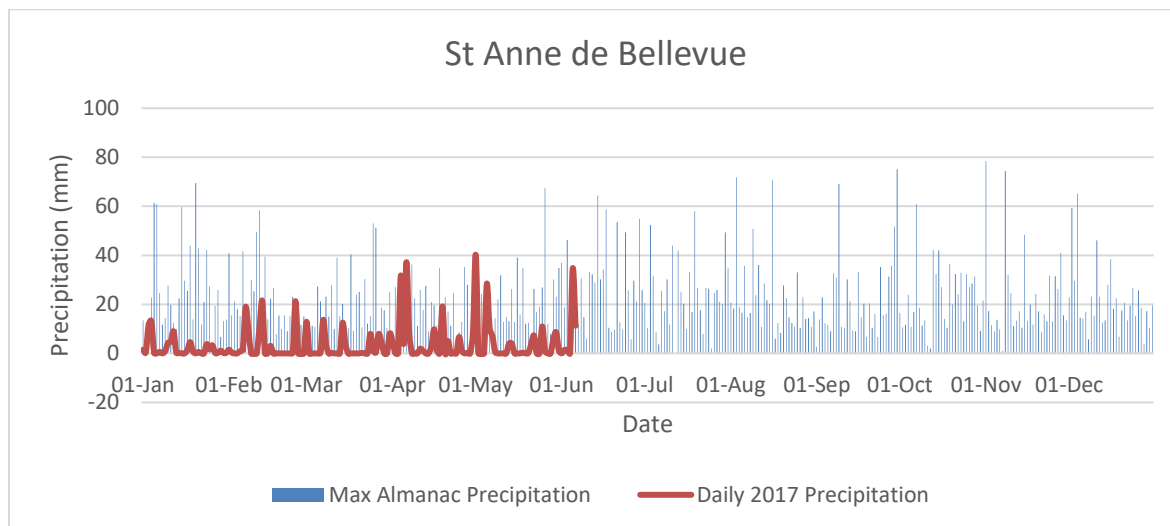
The IJC, 2017 reported that the outflows from Lake Ontario was regulated six times in February because of freezing and thawing of ice cover in the St. Lawrence River. They further reported that by February 26<sup>th</sup>, 2017 most of the ice cover was gone from the St Lawrence which resulted in increased flows from Lake Ontario.

The Lake Ontario – St Lawrence River system continued to experience a series of storm events from March through April 2017 resulting in significant precipitation across the region (IJC 2017). Figure 16 shows that for April 4 to 10, 2017, some parts of the Lake Ontario Basin received as much as 80mm of rainfall, while areas around the St Lawrence River near Montreal saw as much as 90mm during the same series of events.

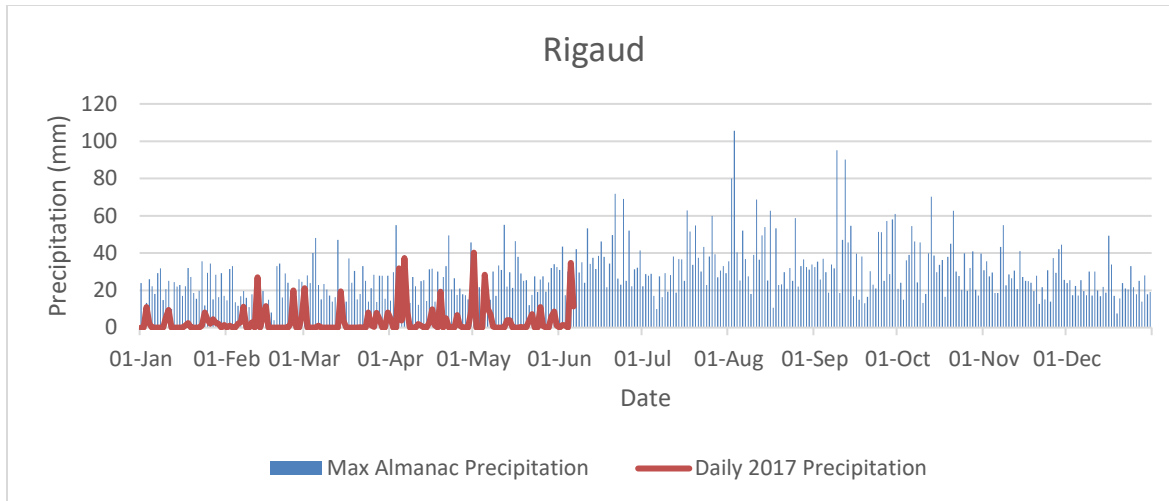


*Figure 16 - Map Showing Total Precipitation Accumulation April 4 – 10, 2017 (Environment Canada 2017)*

This is further illustrated in figures 17 and 18 which shows the comparison of the daily precipitation for 2017 compared with the daily historical maximums for weather stations at Rigaud and Sainte Anne de Bellevue. It can be seen from these figures that for early March, April and May there were precipitation events that were close to the daily historical maximums.



*Figure 17 – Comparison of Average daily 2017 precipitation compared to the daily historical maximums for Sainte Anne de Bellevue*

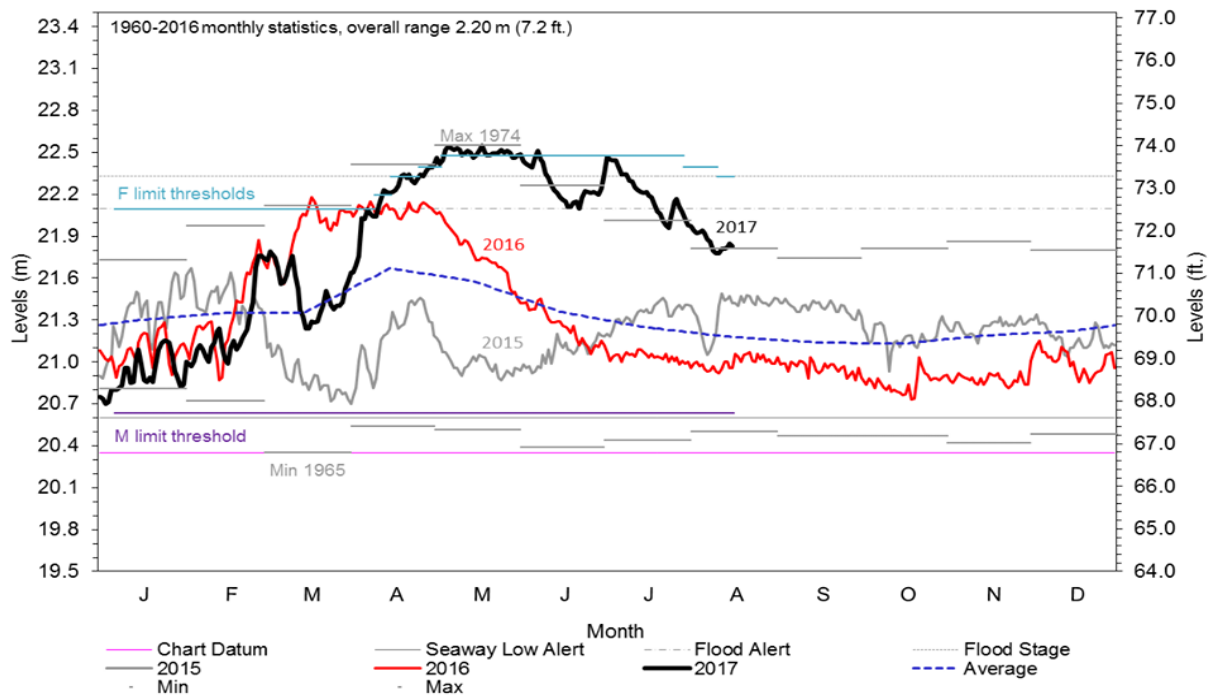


*Figure 18 – Comparison of Average daily 2017 precipitation compared to the daily historical maximums for Rigaud*

## 5.2 Historical Recorded Water Levels

Figure 19 shows us that the F limit threshold level (table 2) of 22.1m or flood alert level was surpassed during the first week of April and continued to rise due to record inflows into Lake Ontario during the same time and increased flows from the Ottawa River (fig.21).

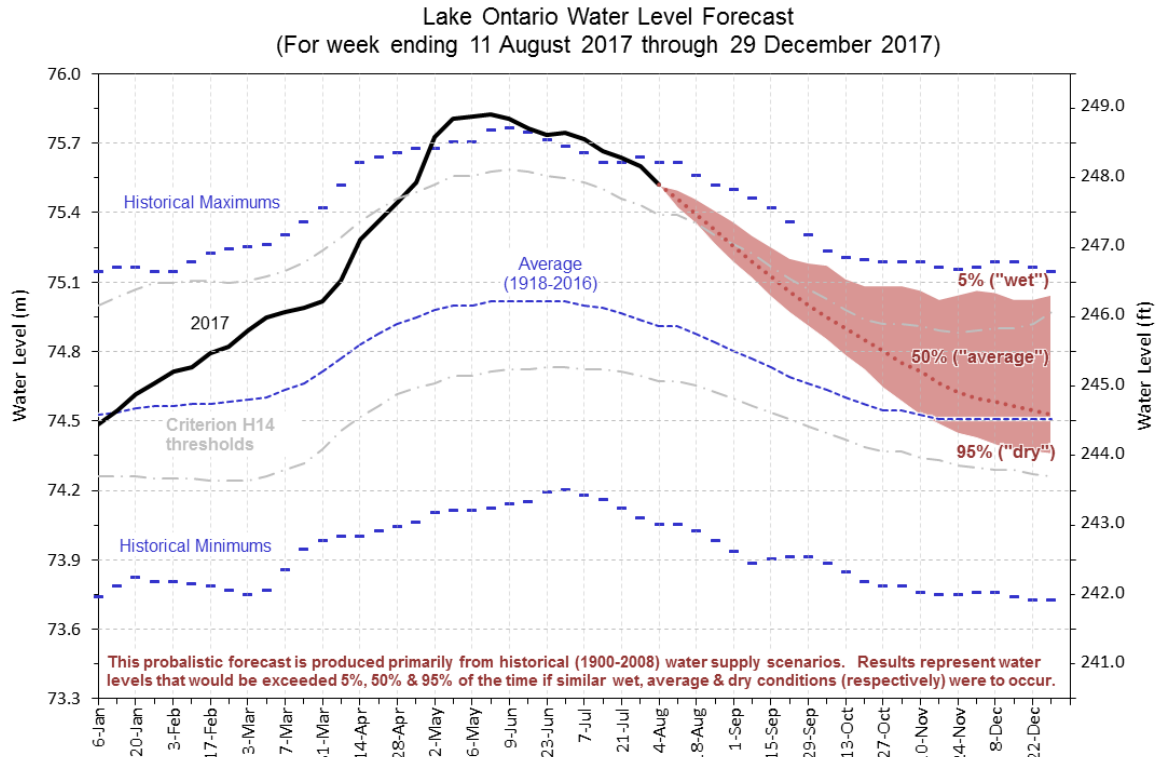
The Great Lakes Connection highlighted that during that time and with record inflows into Lake Ontario, it would have required an increase in outflows of more than  $6000\text{m}^3/\text{s}$  above the average flow to maintain the Lake at a stable level. The result of a flow increase of that magnitude (although impossible) would have directly resulted in flooding of downstream areas causing a rise of 1m in Lac St Louis (IJC 2017).



*Figure 1919 – Flood Hydrograph for Lac St Louis at Pointe Claire (IJC 2017)*

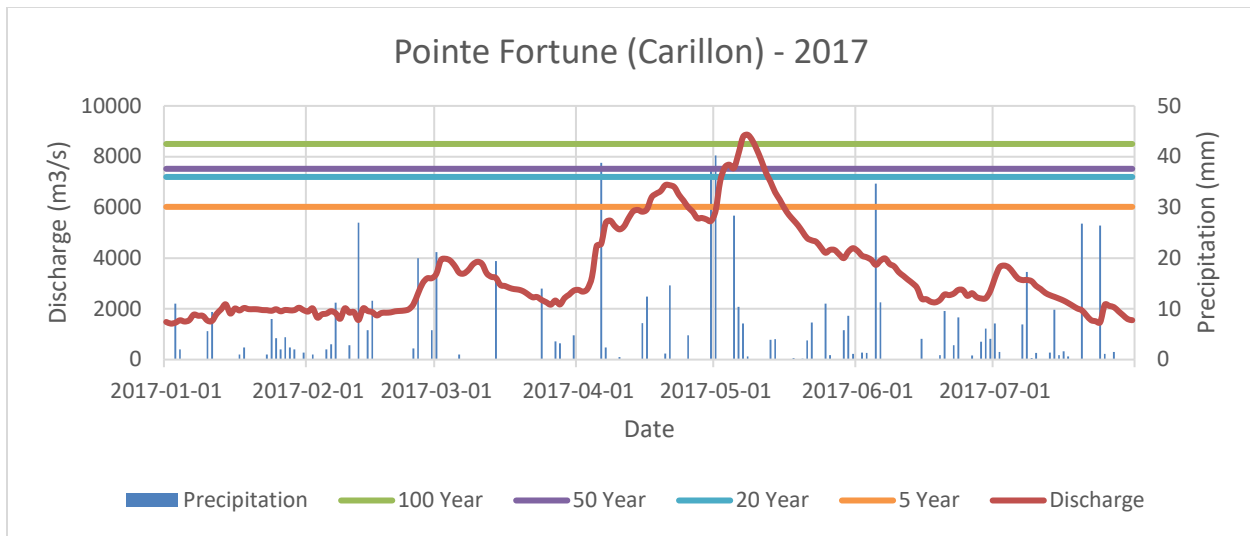
To prevent further increase in water levels at Lac St Louis and causing further damage, the International Lake Ontario – St Lawrence Board reduced outflows from Lake Ontario in accordance with Plan 2014 (table 2). The International Joint Commission reported that the total inflow into Lake Ontario for the month of April 2017 was the second highest recorded since the year 1900.

Figure 20 shows that the upper H14 criterion was reached on April 28, 2017. Criterion H14 is a rule which is part of Plan 2014, that when exceeded, the board is authorized to follow an alternative strategy and release outflows to mitigate the effects of flooding that may affect riparians along the shorelines of the entire river system (IJC 2017).



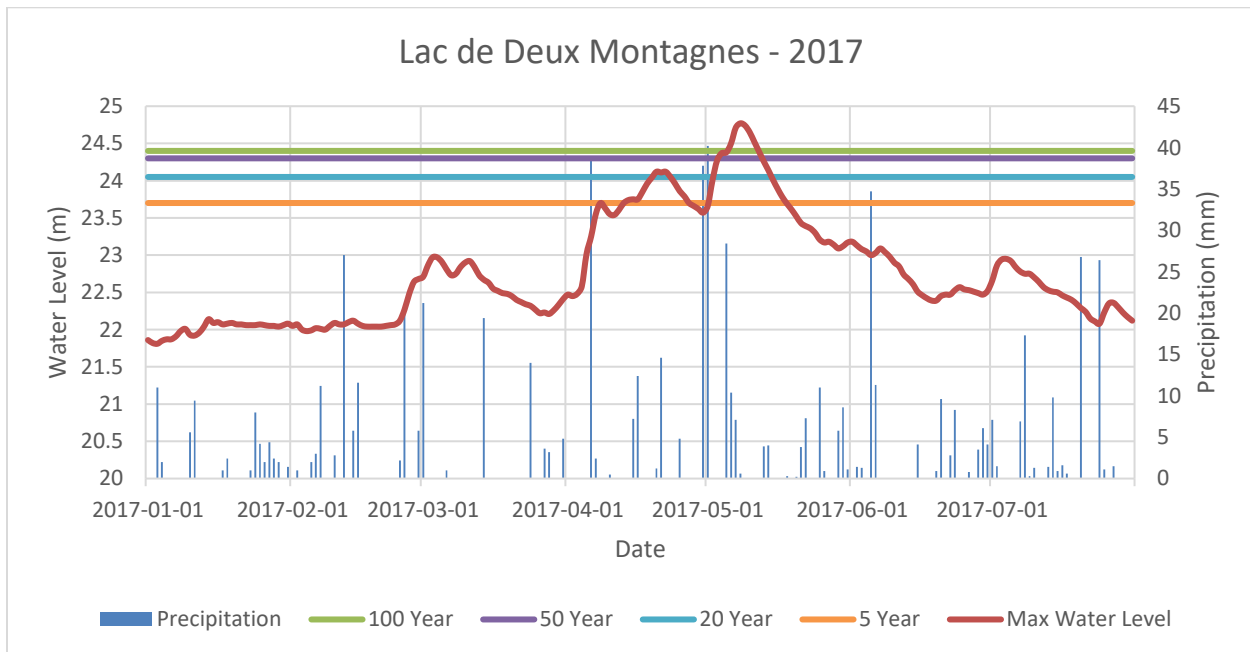
*Figure 20 – Flood Hydrograph for Lake Ontario.*

With 30 storage reservoirs having a combined holding capacity of more than 14 billion cubic meters (ORRPB 2017), one should expect that the Ottawa River basin would suffice to contain yearly flood waters in the river system. At Carillon, the flow rates corresponding to the 5, 20, 50 and 100 years return periods were all surpassed by the end of the first week of May 2017 (figure 21). The highest previously recorded flows at the Pointe Fortune gauging station in the Ottawa River was 8105 m<sup>3</sup>/s in 1974 and 8190 m<sup>3</sup>/s in 1976. The peak discharge of 8861.79 m<sup>3</sup>/s was observed on May 8<sup>th</sup>, 2017 which is the highest ever recorded at that gauging station and coincides with literature for the time of the year when the greatest flood peaks occur (fig.6).

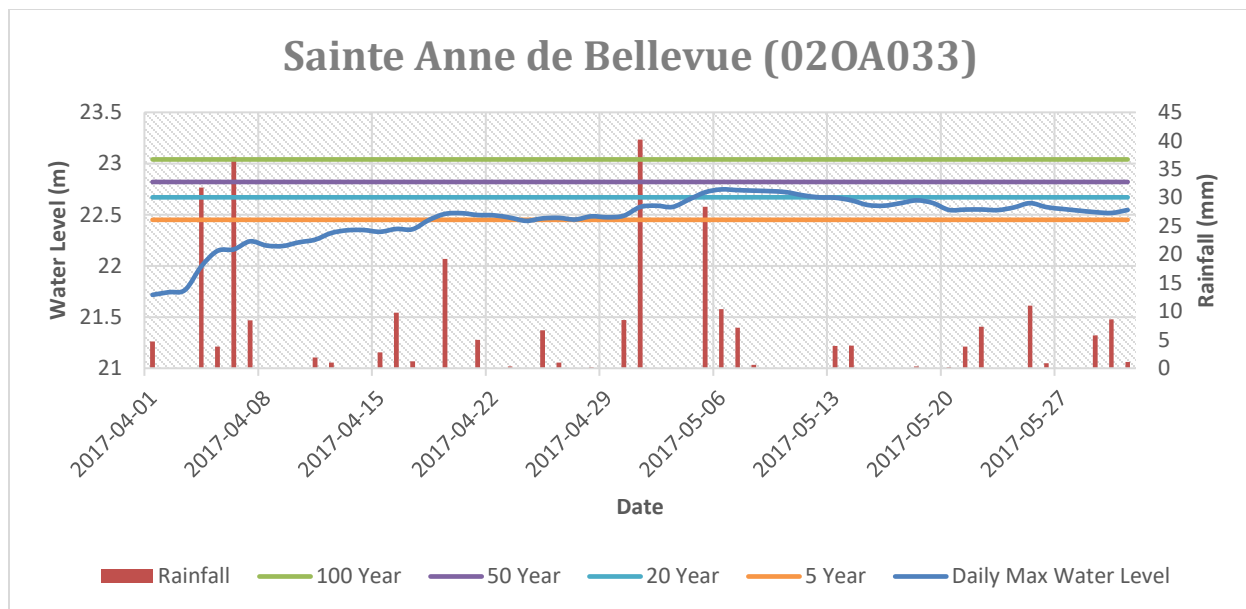


*Figure 21 – Flood Hydrograph of Ottawa River at Carillon (Jan. 1 to July 31, 2017)*

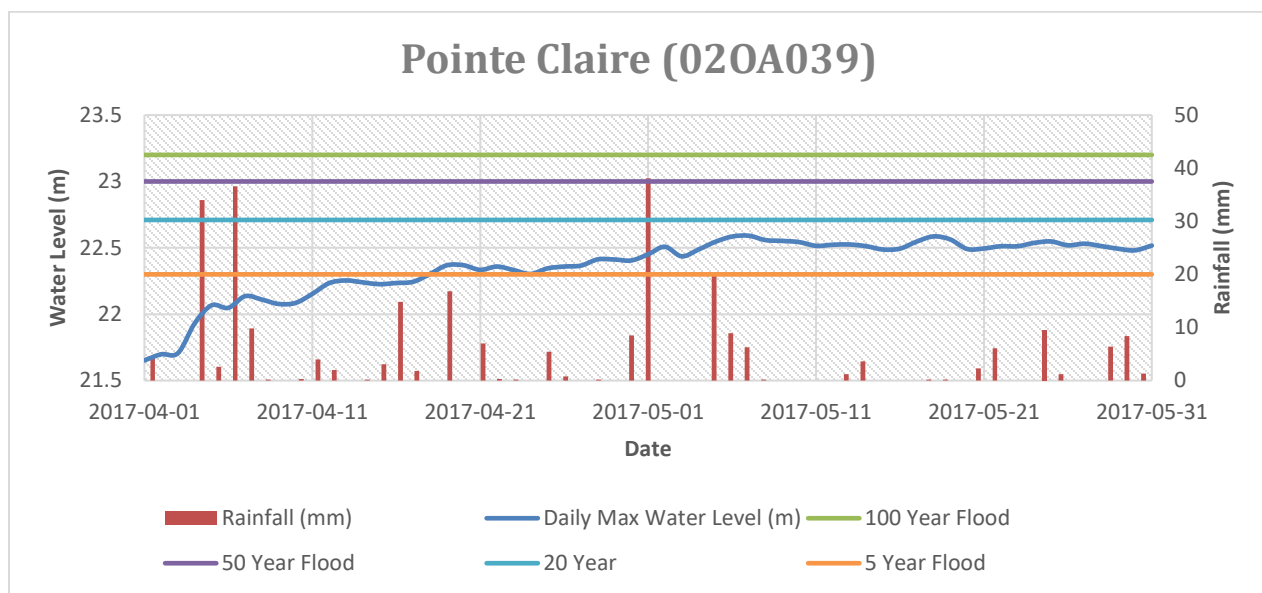
If the two hydrographs in figures 21 and 22 were to be compared the discharge of the Ottawa River and the rate of rise and fall of Lac de Deux Montagnes are comparable having similar peaks and trends. The water level in this lake also peaked on May 8<sup>th</sup>, 2017 to a maximum level of 24.77m which is above the 100-year return level of 24.4m.



*Figure 202 – Flood Hydrograph of Lac de Deux Montagnes (Jan. 1 to July 31, 2017)*



*Figure 23 - Flood Hydrograph for Ste Anne de Bellevue (April 1 to May 31, 2017)*



*Figure 214 - Flood Hydrograph for Pointe Claire (April 1 to May 31, 2017)*

To better understand the flows of water surrounding Montreal, figures 23 and 24 were compared with the hydrograph for Lac de Deux Montagnes to see a trend in water levels. The peak flood levels at Lac de Deux Montagnes were recorded on May 8<sup>th</sup>, 2017 with a level of 24.77m, whereas the peaks at Ste Anne de Bellevue and Pointe Claire for the same day were recorded as 22.739m and 22.58m respectively. This shows that the flows from the Ottawa River directly affect the

levels of Lac de Deux Montagnes and Lac St Louis which validates the flow diagram as shown earlier in figure 3 of this report.

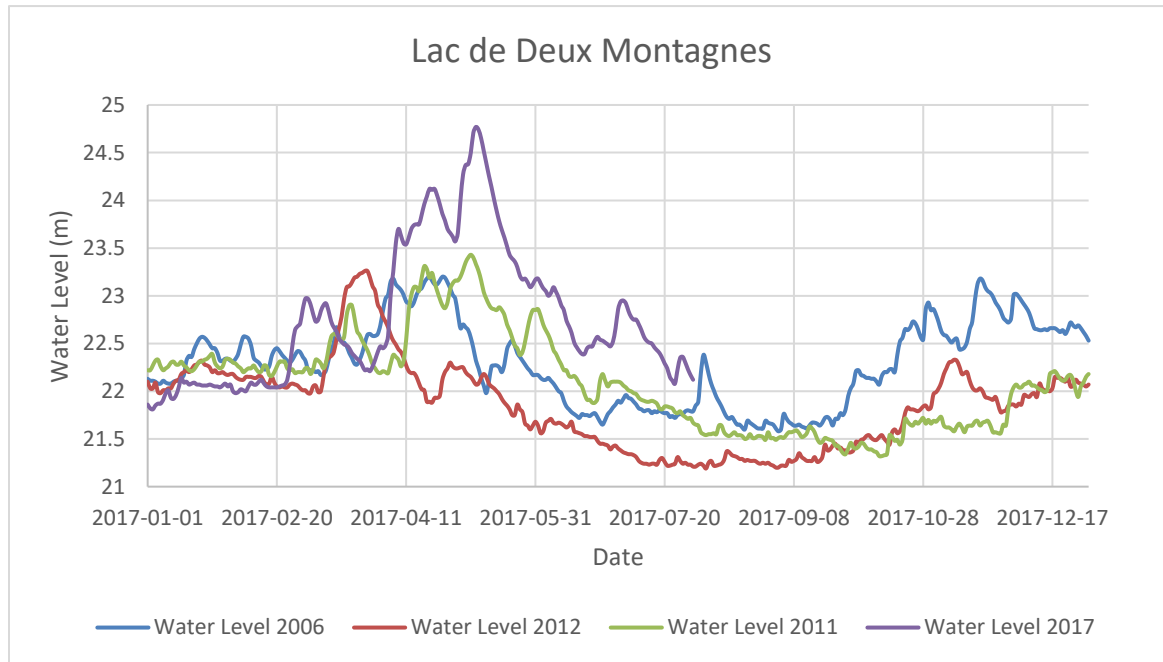
Table 4 shows us that the total precipitation of 422.2mm was experienced before the peak water level at Lac de Deux Montagnes which is way above the average total accumulated precipitation of 275mm for that time of the year (fig. 7). It further shows us that for the period 2010 to 2016, the year 2006 was the wettest year with a total accumulated precipitation of 1335.9 mm and 2012 was the driest with 926.6mm of total accumulated precipitation.

The flood hydrographs for these years were analyzed with the daily hydrograph for 2017 along with the year 2011 and there was not much difference with the flood peaks experienced for the wet and dry years (fig. 25) and for 2011 which are all below the 5 year flood level of 23.7m but differs significantly from the 2017 hydrograph. The similarity in peaks for 2006, 2011 and 2012 tells us that for those years the flows were controlled perfectly in the Ottawa River system which dictates the levels in Lac de Deux Montagnes disregarding whether it was a wet or dry year. This also tells us that the inflow forecasting model used by the ORRPB as a guide to the decision-making process to assists the operators in the release of flows from each control facility to maintain flood control did not work for the wet and warm winter that was experienced which rapidly transitioned into a wet spring as record historical flows were recorded at the outflow of the Ottawa River.

*Table 5 – Annual Precipitation for Weather Station at Rigaud*

<b>Year</b>	<b>Total Precipitation (mm)</b>
<b>2006</b>	1335.9
<b>2007</b>	1038.1
<b>2008</b>	928.1
<b>2009</b>	957.2
<b>2010</b>	1155.7
<b>2011</b>	1116.4
<b>2012</b>	926.6
<b>2013</b>	1031.6
<b>2014</b>	1035.3
<b>2015</b>	1058.7
<b>2016</b>	1045.4

**Jan 1, 2017 to May 8, 2017**



*Figure 25 – Water Levels for Lac de Deux Montagnes*

## 6.0 Conclusions

Warm temperatures coupled with precipitation events created a freezing and thaw effect within the St Lawrence and Ottawa River Basins since January 2017. At Rigaud and Sainte Anne de Bellevue the temperatures rose above 0°C two times between the 11<sup>th</sup> January and the 23<sup>rd</sup> of January. This warm winter weather continued in February with more days above freezing point compounded with snowfall. Since the temperatures were above 0°C for the days with almost maximum daily historical precipitation, the snowfall melted and made its way into the rivers and streams.

From the analysis in this study it was seen that for the months of March, April and May there were precipitation events that were close to the daily historical maximums which adds to the conclusion that the warm winter season transitioned into a wet spring. Total accumulated precipitation of 422.2 mm of precipitation was experienced before the flood peak of 24.77m recorded at the Lac de Deux Montagnes gauging station which was way above the total average precipitation for that time of the year.

The F limit threshold level as stipulated by Plan 2014 of 22.1m or flood alert level was surpassed during the first week of April and continued to rise due to record inflows into Lake Ontario during the same time and increased flows from the Ottawa River system.

To prevent further increase in water levels at Lac St Louis and causing further damage, the International Lake Ontario – St Lawrence Board reduced outflows from Lake Ontario in accordance with Plan 2014. Plan 2014 was implemented to balance the impacts of flooding both upstream and downstream of the river system by limiting the effects of flooding around the Lac St Louis area however it cannot and does not eliminate the risks that high levels may occur during periods of extreme weather as experienced through the year 2017.

Water levels and discharges recorded at Pointe Fortune (Carillon), Lac de Deux Montagnes, Pointe Claire and Lake Ontario surpassed historical levels that resulted in the May 2017 flooding event in Montreal and surrounding areas. Discharge at Pointe Fortune (Carillon) was recorded at 8862.71 m<sup>3</sup>/s the highest recorded in history at that point in the Ottawa River.

It was noticed that although the year 2006 was considered a wet year with above average precipitation and 2012 a dry year with below average precipitation, there was no major difference in the flood peaks recorded at the gauging station for Lac de Deux Montagnes which concludes that the flows were perfectly controlled in the Ottawa River system for those years.

From this study, it can be concluded that the May 2017 flooding events in Montreal and surrounding areas were as a direct result of the above normal weather that was experienced. It can be further concluded that the inflow forecasting model used by the ORRPB as a guide to the decision-making process to assist the operators in the release of flows from each control facility to maintain flood control did not work for the wet and warm winter that was experienced which rapidly transitioned into a wet spring as record historical flows were recorded at the outflow of the Ottawa River which directly influenced flooding of Montreal and surrounding areas.

## References

Environment Canada. 2017. *Environment and Climate Change Canada*. August 4. Accessed August 5, 2017. <https://www.ec.gc.ca/stl/default.asp?Lang=En&n=F46CF5F8-1>.

Farvolden R.N., Plannkuch o., Pearson R., and Fritz P. 1988. *Region 12, Precambrian shield. The Geology of North America. V-O.2*. Boulder, Colorado: Geological Society of America.

- IJC. 2017. *Great Lakes Connection*. August 10. Accessed August 10, 2017.  
<http://ijc.org/greatlakesconnection/en/tag/flooding>.
- International Joint Commission. 2014. "IJC." *Lake Ontario - St Lawrence River Plan 2014*. June. Accessed August 5, 2017. [http://www.ijc.org/files/tiny\\_mce/uploaded/LOSLR/IJC\\_LOSR\\_EN\\_Web.pdf](http://www.ijc.org/files/tiny_mce/uploaded/LOSLR/IJC_LOSR_EN_Web.pdf).
- International St Lawrence River Board of Control. 2017. *Lake Ontario Outflow Strategy*. Accessed August 18, 2017. <http://www.islrbco.org/new-Version/strategy/strategy04-01-16.html>.
- James H. Thorp, Gary A. Lamberti, and Andrew F. Casper. 2005. "St. Lawrence River Basin."
- Ontario Water Resources Commission and Quebec Water Board. 1971. *Ottawa River Basin, Water Quality and its control in the Ottawa River*. Ottawa: Environment Canada.
- ORRPB. 2017. "Ottawa River Regulation and Planning Board." August 5. Accessed August 5, 2017.  
<http://ottawariver.ca/ottawa-river-carillon.php>.
- Ottawa River Heritage Designation Committee. 2005. *A Background Study for Nomination of the Ottawa River*. Canadian River Heritage System.
- Quebec Government, Centre d' Expertise hydrique. 2017. *Ministère du Développement Durable de l'Environnement et de la lutte contre les changements climatiques*. Accessed May 15, 2017.  
[https://www.cehq.gouv.qc.ca/hydrometrie/historique\\_donnees/ListeStation.asp?regionhydro=04&Tri=Non](https://www.cehq.gouv.qc.ca/hydrometrie/historique_donnees/ListeStation.asp?regionhydro=04&Tri=Non).
- Revenge, C., S. Murray, J. Abramovitz, and A. Hammond. 1998. "Watersheds of the world: ecological value and vulnerability." *World Resources Institute*.
- The International St Lawrence River Board of Control. 1963. "Regulation of Lake Ontario. Plan 1958 - D."
- The National Academies Press. 2017. "Review of Lake Ontario - St Lawrence River Studies (2006)." *The National Academies of Science Engineering Medicine*. Accessed August 17, 2017.  
<https://www.nap.edu/read/11481/chapter/3>.