Toronto Islands Flood Characterization and Risk Assessment Project

Flood Characterization Report

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Toronto Islands Flood Characterization and Risk Assessment Project

Flood Characterization Report

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Revision	Date	Status	Comments	Prepared	Reviewed	Approved
A	2018/10/01	Draft	TRCA Review	JJF/YK	JDW	RBN
B	2019//02/04	Draft	TRCA Review	JDW	RBN	RBN
0	2019//03/12	Final	Final	JDW	RBN	RBN

Executive Summary

Baird & Associates (Baird) was retained by Toronto and Region Conservation Authority (TRCA) to undertake a flood characterization and risk assessment for the Toronto Islands. This first report reviews the conditions that led to the 2017 high water levels on Lake Ontario; updates the return period water levels at Toronto; evaluates the impacts of the change in Lake Ontario regulation plans on the return period water levels; and reviews recent climate change research related to future Lake Ontario water levels. The second report will quantify damages resulting from the return period flood events, and the third report will evaluate structural options to mitigate the flood risk.

The 2017 high water levels were the result of extreme wet weather in the Lake Ontario basin, record inflows from Lake Erie, and reduced outflow capacity due to downstream flooding on the St. Lawrence and Ottawa rivers. Daily average water levels at Toronto were the highest ever recorded, exceeding the May 1973 and May 1993 high water levels by 0.16 and 0.26 m, respectively. Water levels remained above the 100-year flood level from May 7 to July 9, 2017, a period of 63 days. The sustained period of high water levels resulted in approximately $8M in direct and indirect damages to the City of Toronto related to the closing of Toronto Island Park.

Return period water levels developed by the Ontario Ministry of Natural Resources (OMNR, 1989) were reviewed and updated using 57 years of measured water level data (1962-2018). The analysis indicates that the 100-year return period static (monthly) water level for Lake Ontario should be increased by approximately 0.2 m. Return period storm surge (wind setup) estimates for Toronto were slightly lower than the values in OMNR (1989). Stillwater levels, which represent the probability of all combinations of static lake levels and storm surge are estimated to be approximately 0.2 m higher than reported in OMNR (1989).

The International Joint Commission (IJC) implemented a new regulation plan for the St. Lawrence Seaway and Lake Ontario in 2017. The plan is known as Plan 2014 and replaces Plan 1958DD (with deviations), which has been in place since 1963 (note that Plan 1958A was implemented in 1960). Baird reviewed simulated water levels by Environment Canada under both plans for the period of 1900 to 2008. The simulations indicate that spring high water levels (with return periods ranging from 2 to 100 years) will increase by approximately 0.05 to 0.15 m under the new plan. The highest increases in spring high water levels (i.e. 0.15 m) occur for moderate floods with return periods of 10 and 25 years. The plans are nearly identical at extreme high water levels, and any difference in water levels is related to how the plans function before extreme high water levels are reached. Plan 2014 is estimated to result in an increase of 0.07 m to the 100-year flood level.

It is recommended that the 100-year flood level for Toronto Islands, which is defined as the 100-year stillwater level, be increased from 75.74 to 76.05 m IGLD85. Twenty-four centimeters of the increase is attributed to the use of observed water levels from the post-regulation era (e.g. 1962 to 2018) and ignoring the adjusted pre-regulation water levels in the analysis. The remaining seven centimeters of the increase is attributed to the change in regulation plans. The highest hourly water level recorded at the Toronto Harbour gauge is 75.98 m IGLD85 (June 4, 2017). These findings are consistent with the recommendations in the Toronto Islands Shoreline Management Study (Baird, 1994), which identified concerns with the OMNR (1989) flood levels for Toronto and recommended that the 100-year flood level for Toronto be increased to 75.95 m IGLD85.

The latest climate change research related to precipitation, evaporation, snow and ice cover, and storminess in the Lake Ontario basin were reviewed to estimate potential future changes to static water levels, storm surge, and waves at Toronto Islands. Current research suggests that water levels in the Great Lakes will remain similar or decline slightly due to increased evapotranspiration. The anticipated impacts of climate change on

static water levels are less than the natural variability of long-term lake levels, and will likely be manageable within the current regulation plan. Furthermore, the International Joint Commission's Great Lakes-St. Lawrence River Adaptive Management Committee will review, update, and track information on water levels and hydrologic conditions that might influence how outflows from Lake Ontario will be managed in the future. Therefore, at this time we do not recommend any increase or decrease in the 100-year static water level due to climate change.

There is low confidence in future projections of how wind speeds and wind patterns might be affected by climate change. Future increases in wind speed could result in larger waves and storm surges in Lake Ontario. Storm surge at Toronto is low compared to other locations on the Great Lakes.

Baird's Lake Ontario wave hindcast (1961-2010) was used to evaluate offshore and nearshore wave conditions at Toronto Islands. Wave runup, overtopping, and inland excursion of overtopping waves were calculated for the 100-year event using the combined probability of different combinations of return period waves and stillwater levels. The results of the wave uprush analysis are similar to the Shoreline Management Study (Baird & Reindeers, 1994a), which recommended a 5 m horizontal setback (from the 100-year flood elevation contour) along the Inner Harbour, and a 15 m horizontal setback from the Centre Island seawall.

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1. Introduction & Study Objectives

Baird & Associates (Baird) was retained by Toronto and Region Conservation Authority (TRCA) to undertake a flood characterization and risk assessment for the Toronto Islands. The overall project objective is to develop conceptual designs, costs, and estimates of annualized reductions in flood damages for various flood mitigation alternatives. The project deliverables will include three reports and one set of emergency response maps. The assessment will consist of the following four main parts:

- **Flood Risk Characterization:** review the conditions that led to the 2017 flooding and re-evaluate return-period extreme lake levels in light of recent data and climate change science.
- **Flood Risk Assessment:** quantify tangible and intangible damages resulting from the return-period flood risk events.
- **Flood Response Plan:** develop emergency mapping based on input from the City of Toronto and TRCA.
- **Flood Mitigation Alternatives:** develop conceptual designs to mitigate the flood risk and quantify annualized expenditures or savings resulting from mitigation works.

This first report reviews the hydrological conditions that led to the 2017 high water levels; reviews and updates the return period water levels using the last 57 years of measured water level data (1962-2018); and evaluates the impacts of the change in regulation plan and future climate on lake levels.

1.1 Water Level Definitions

This report uses of the following definitions from Ontario Ministry of Natural Resources (OMNR, 1996):

100-year flood level – the peak stillwater level due to the combined occurrences of mean monthly lake levels and wind setup having a total probability of 1% of being equalled or exceeded during any year.

Static water level – elevation of surface of the water in the absence of wind, wave, atmospheric and/or tidal disturbances.

Storm surge (wind setup) – a rise above the normal static water level on the open coast due to the action of wind stress on the water surface.

Stillwater level – the elevation that the surface of the water would assume if wind setup and other atmospheric and/or tidal displacements of the water body occurred, but wave action was absent.

Wave setup – super-elevation of the water surface, averaged over time shoreward of the breaking point, over normal surge elevation due to onshore mass transport of the water by wave action alone.

1.2 Note on Elevations and Datums

Unless otherwise noted, all water levels are reported in International Great Lakes Datum 1985 (IGLD85). IGLD85 is 8.4 cm below Canadian Geodetic Vertical Datum 1928-1978 Ontario Adjusted Version (CGVD 1928:1978), and 49.6 cm below Canadian Geodetic Vertical Datum 2013 (CGVD 2013) at the Canadian Hydrographic Service benchmark 0011959U9526 (also known as 00159U9526, 59U9526, and TORO 1-1959). The benchmark is located at the Toronto Harbour Gaugehouse at the south side of Queen's Quay. The elevation of the benchmark relative to the different datums is shown in Figure 1.1. Benchmark information from Ontario's Control Survey Information Exchange (COSINE) and Canadian Hydrographic Service is provided in Appendix A.

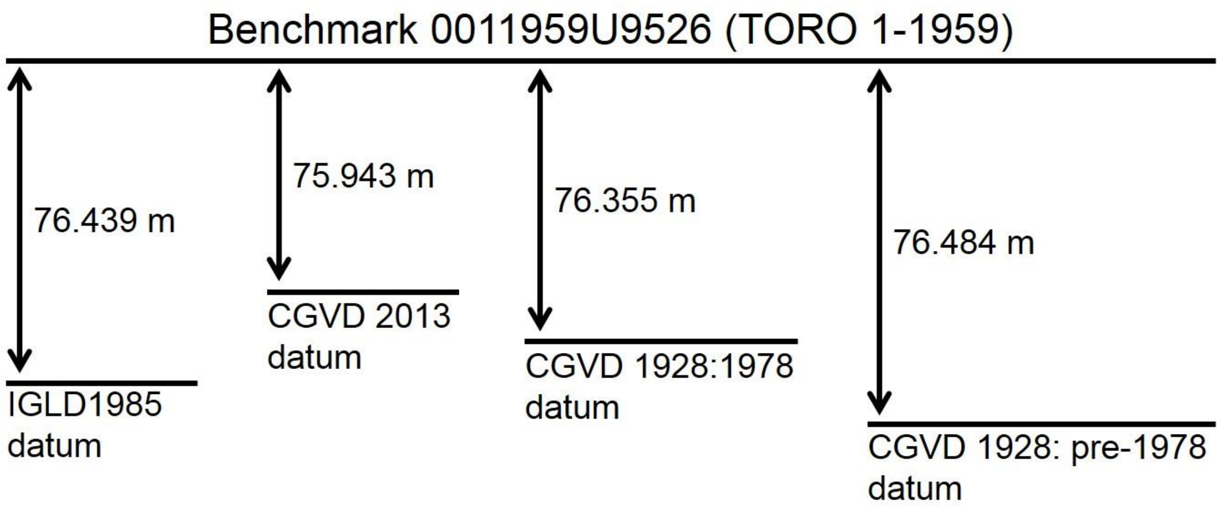


Figure 1.1: Elevation of the Toronto Harbour Gaugehouse Benchmark

The return period water levels in Ontario Ministry of Natural Resources (1989) are reported in International Great Lakes Datum 1955 (IGLD55) and Canadian Geodetic Vertical Datum 1928:pre-1978 datum. The difference between IGLD 1955, IGLD 1985, and CGVD28 at the holding benchmark for Toronto is provided in Table 1.1.

Table 1.1: Differences between IGLD and CGVD at Toronto (from OMNR, 1996)

Benchmark Number	IGLD85 - IGLD55 (m)	IGLD85 - CGVD28 (m)	CGVD28 - IGLD55 (m)
579-F	0.13	0.05	0.08

2. Lake Ontario Water Levels

Lake Ontario water levels are generally highest in the spring and early summer, due to snowmelt, increased precipitation and inflows from Lake Erie (see Figure 2.1). The average water level from May through July is 75.1 m. The highest monthly water level for Lake Ontario was set in June 2017 (75.81 m), and the highest daily water level (lakewide) was set in late May (75.88 m). The highest hourly water level at Toronto was observed on June 4, 2017 (75.98 m). Lake levels were above the 100-year flood level for approximately one month is 1973 and two months in 2017.

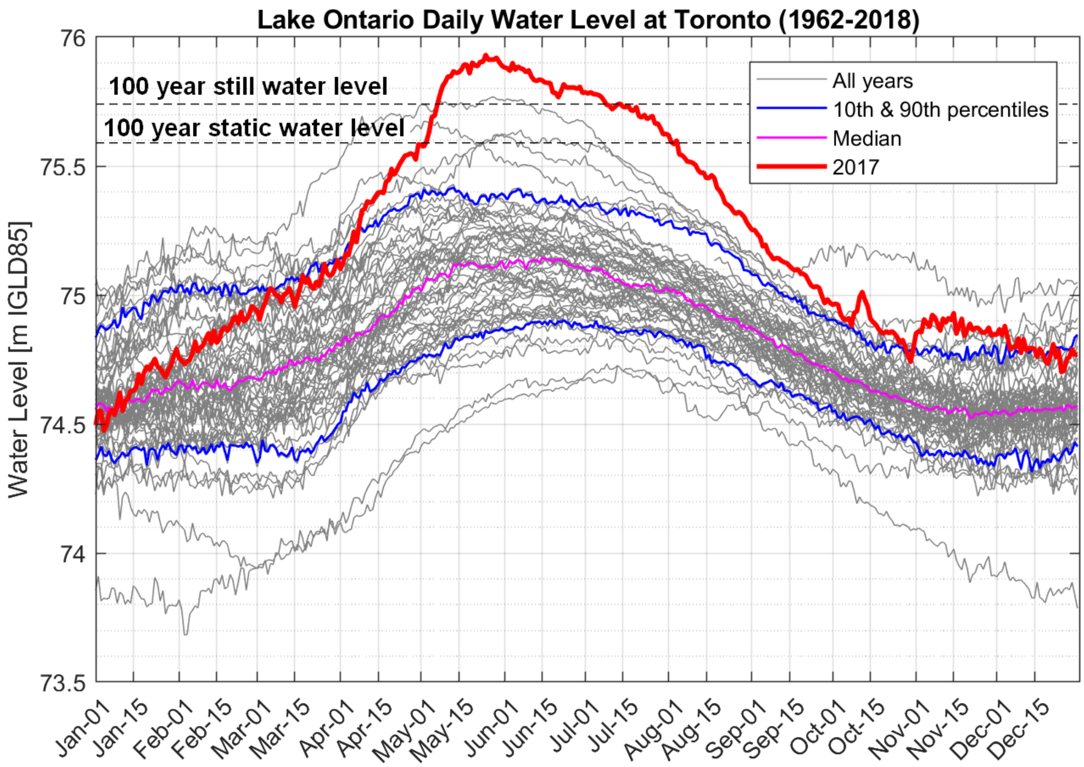


Figure 2.1: Daily Water Levels at Toronto 1962 to 2018

2.1 Historical Water Levels

Quarter-monthly observed water levels for Lake Ontario were provided to TRCA by Environment Canada (personal communication, J. Bruxer, 15 February 2018). The dataset consists of lake-averaged water levels for the beginning of the quarter month from 1900 to 2017 (48 measurements per year). Monthly mean water levels are also available from Fisheries and Oceans Canada from 1918 to present.

The St. Lawrence Seaway was completed in 1959 and water levels in Lake Ontario have been regulated by the International Joint Commission (IJC) since that time. The first regulation plan, Plan 1958A, came into effect in 1960. This plan was subsequently revised to improve low water conditions at the Port of Montreal and address severe drought conditions in the mid 1960s. The regulation plan that was in effect between 1963 and 2017 is known as Plan 1958DD (which includes plan deviations).

In January 2017 a new regulation plan, Plan 2014, was implemented after 14 years of scientific study and public engagement. The new plan aims to restore wetland ecosystems by returning water levels to a more natural cycle. The plan balances the needs of various upstream and downstream uses including shore protection, flooding, shipping, fishing, recreation, hydroelectric production, and cultural and environmental interests. Monthly water levels for Lake Ontario pre- and post-regulation are shown in Figure 2.2.

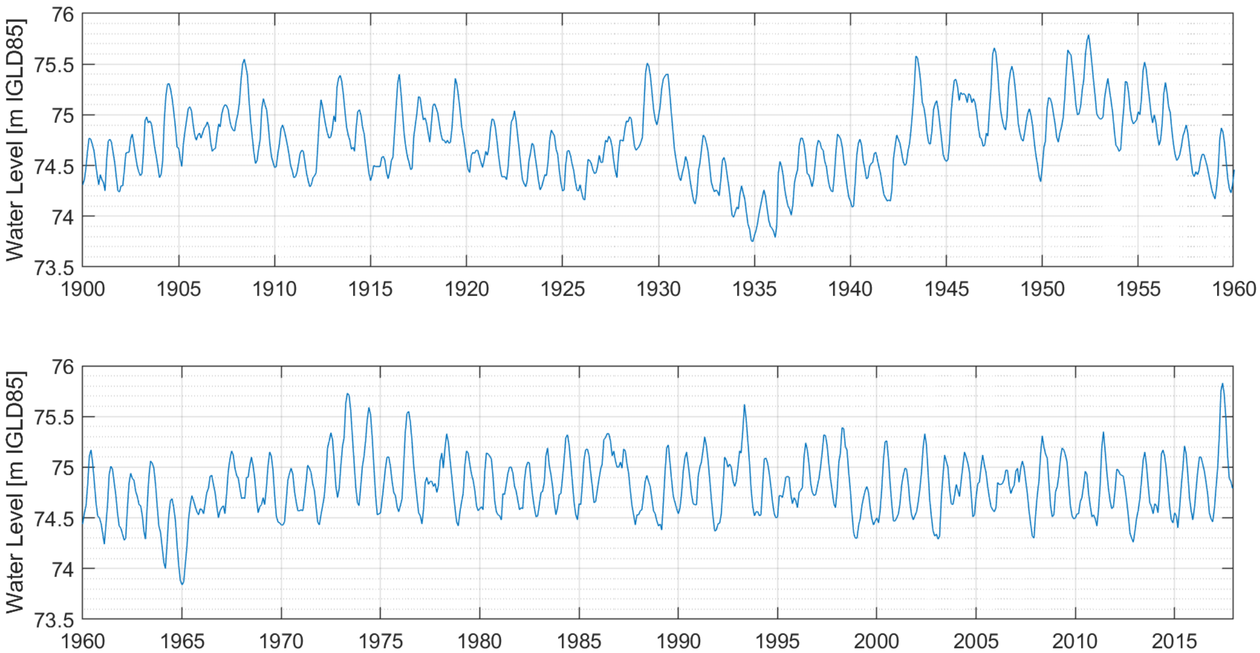


Figure 2.2: Lake Ontario Monthly Water Levels (pre-regulation top panel; post-regulation bottom panel)

Prior to regulation, water levels in Lake Ontario were more variable and could remain at high or low levels for several consecutive years. Regulation reduced this trend, providing more consistent annual water levels. However, the ability to regulate water levels during extremely wet or dry periods is limited. Table 2.1 shows that the extreme low and extreme high water levels pre- and post-regulation are similar.

Table 2.1: Lake Ontario Minimum and Maximum Monthly Mean Water Level Pre- and Post-Regulation

Period	Minimum Monthly Mean Water Level (m IGLD85)	Maximum Monthly Mean Water Level (m IGLD85)
Pre-regulation (1900-1960)	73.74 (Dec 1934)	75.76 (Jun 1952)
Post-regulation (1960-2017)	73.83 (Jan 1965)	75.81 (Jun 2017)

2.2 Net Basin Supplies

Lake Ontario water levels depend on the volume of water flowing into and out of the lake and evaporation. About 80-85% of the inflows come from Lake Erie, with the remaining amount falling as precipitation on the lake's surface or within the drainage basin. Net water supplies follow natural cycles that have timescales ranging up to decades. For example, the severe drought of the 1930s resulted in the lowest water supplies to Lake Ontario since 1860 (see Figure 2.3). Higher water supplies returned in the 1950s, followed by another drought in the 1960s. The 1970s, 1980s, and 1990s were wetter than average. Net basin supplies from 2000 to present have been near the long-term average. The causes of the long-term wet/dry cycles are not fully understood (IJC, 2014); however, it is believed that the cycles may be driven by large-scale atmospheric and oceanic circulation patterns (Hanrahan et al., 2014; Watras et al., 2014).

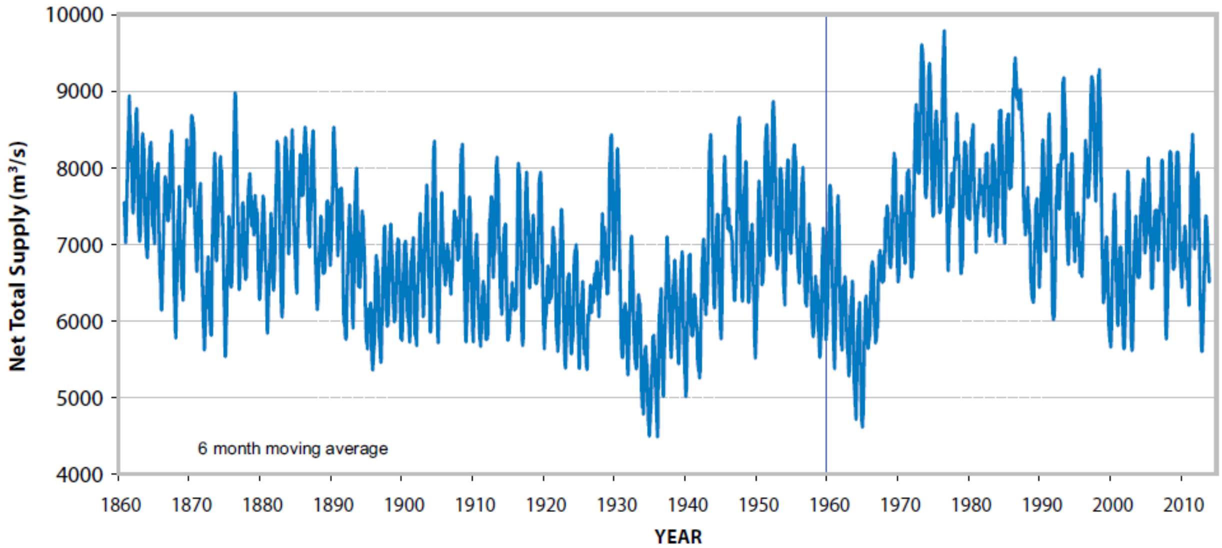


Figure 2.3: Lake Ontario Net Total Supplies 1860-2013 (from IJC, 2014)

2.3 Simulated Monthly Water Levels

Environment Canada provided TRCA (personal communication, J. Bruxer,15 February 2018) simulated quarter-monthly water levels for Lake Ontario from 1900-2008 under Plan 1958DD, Plan 2014, and Pre-project conditions (see Figure 2.4). The simulations were carried out using the same time series of observed inflows and other inputs that influence the outflow conditions (e.g. flows in the Ottawa River and ice conditions on the St. Lawrence River). Extreme high water levels are lower under both regulation plans than under pre-project conditions.

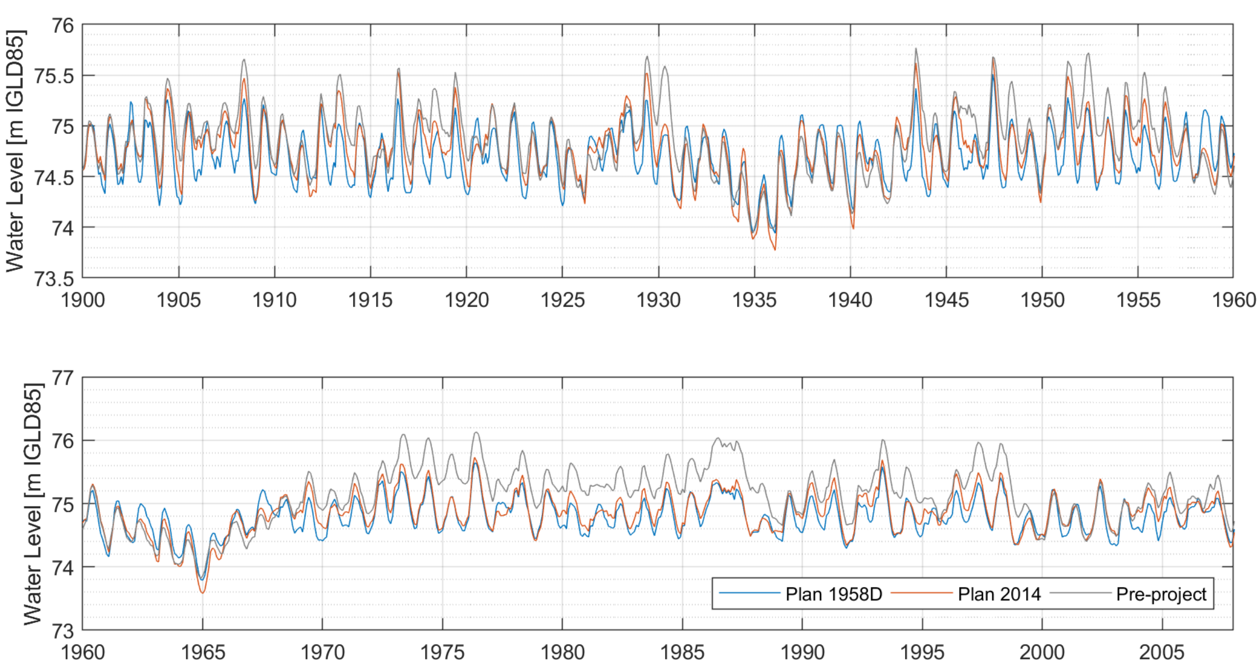


Figure 2.4: Lake Ontario Simulated Water Levels under Plan 1958DD, Plan 2014, and Pre-project

The observed and simulated water levels for the five highest observed monthly water levels (1900-2008) are summarized in Table 2.2 (sorted by date). The Pre-project simulated water levels match the observed high water levels in 1947, 1951, and 1952 well. The Plan 1958DD simulated water levels underestimate the 1973 observation and agree with the 1993 observation. The difference between the simulated and observed 1973 high water levels is due to an underestimation of Lake Erie outflows by the model (Baird, 1994). The Plan 2014 simulated water levels are on average 0.1 m higher than the simulated Plan 1958DD water levels for these five events.

Table 2.2: Summary of Observed and Simulated Extreme Monthly Water Levels

Month	Observed (m)	Simulated Plan 1958DD (m)	Simulated Plan 2014 (m)	Simulated Pre-project (m)
July 1947	75.66	75.51	75.68	75.68
May 1951	75.64	75.28	75.49	75.64
June 1952	75.79	75.18	75.24	75.72
May 1973	75.73	75.50	75.62	76.09
May 1993	75.62	75.58	75.69	76.01

2.4 Regulation Plans

The 1952 and 1956 Orders of Approval for the St. Lawrence River Power Project were the beginning of regulation of Lake Ontario water levels and outflows. Since then, many studies have concluded that regulation caused damage to ecosystems, most notably due to the compression of the range of water levels which caused wetlands to degrade (IJC, 2014).

On December 8, 2016, the IJC issued an order replacing Plan 1958DD with Plan 2014 effective January 7, 2017 (Caldwell, 2017b). Plan 2014 is a combination of mechanistic release rules (called Bv7) and discretionary decisions made by the International Lake Ontario-St. Lawrence River Board (ILOSLRB) to deviate from those rules. Some of the key terms from Plan 2014 are summarized below.

- **I-limit:** An upper limit flow rate to allow for stable ice formation in the St. Lawrence River and reduce the risk of ice jams. The limit is 6,230 m^3/s (IJC, 2016).
- **F-limit:** A flow rate that “balances” flooding upstream and downstream of the Moses-Saunders Dam at Cornwall, Ontario. The balancing strategy is multi-tiered and is based on decisions during high water events in the 1990s. The flow rate is adjusted to balance the water levels in Lake Ontario and Lake Pointe Claire using a lookup table.
- **L-limit:** Defines the maximum outflow that will maintain adequate levels and safe velocities for navigation in the international section of the St. Lawrence River.
- **Criterion H14:** An upper limit water level, beyond which the board is allowed to deviate from Plan 2014 and increase the flows beyond the Rule Curve limits. This water level is defined as the 2% exceedance water level for a particular quarter-month (IJC, 2016).
- **Plan 2014 Rule Curve:** A stage-discharge relationship derived from pre-project (pre-1950s) open water conditions, adjusted to recent long-term supply conditions.

The key difference between Plan 2014 and Plan 1958DD is the increased natural variability of Lake Ontario water levels. However, no significant difference exists between the two plans under extreme weather conditions, as the regulation of outflows becomes determined by safety considerations (I-limit, F-limits, and L-limits) rather than the Plan 2014 rule curve.

3. Review of 2017 Flooding at Toronto Islands

In May 2018, ILOSLRB published a report (ILOSLRB, 2018) describing the unprecedented hydrological conditions in the Lake Ontario and St. Lawrence River basins in 2017. The high water levels in Lake Ontario were attributed to the extremely high water supplies, although other factors such as timing of flows in the Ottawa River and freeze-thaw conditions also played a factor.

In November 2018, the IJC's Great Lakes-St. Lawrence River Adaptive Management (GLAM) Committee published a report (GLAM, 2018a) that addressed concerns including: the influence of the change in regulation plans, the ability to forecast hydrological conditions, comparison with historical inflows and water levels, and IJC's response. The report notes that the water level in Lake Ontario would have peaked within +/- 2 cm of the actual peak in June 2017 had the ILOSLRB been operating under Plan 1958DD instead of Plan 2014 (GLAM, 2018a). The GLAM Committee is tasked with tracking the performance of the regulation plan in meeting its stated objectives and providing information to the ILOSLRB and IJC (as well as International Lake Superior Board of Control and International Niagara Board of Control) for improving water management outcomes.

3.1 Overview

The outflows from Lake Ontario in 2017 are shown with the Plan 2014 rule curve and other considerations in Figure 3.1. The figure highlights the flow reductions that resulted from the winter ice operations and flooding on the St. Lawrence River downstream of Cornwall. Flows in the Ottawa River peaked on May 8 and as the Ottawa River subsided, outflows from Lake Ontario were increased from 6,000 m³/s on May 7 to 10,200 m³/s on May 24.

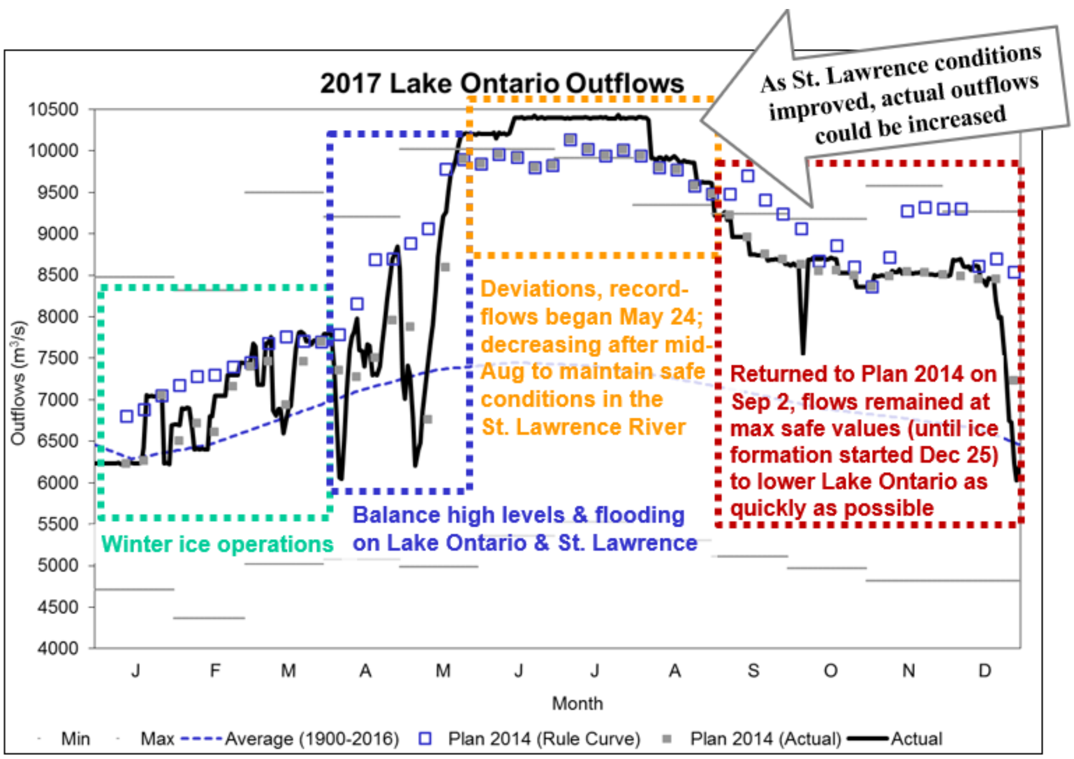


Figure 3.1: Lake Ontario 2017 Outflows (from ILOSLRB, 2017a)

The 2017 Lake Ontario daily water levels are shown with the outflow considerations in Figure 3.2. The figure shows that the 2017 water levels were very similar to the 2016 water levels up until April 1. Between April 1 and May 25, water levels rose sharply due to heavy rainfall in the Lake Ontario basin and flow reductions that balanced upstream and downstream flood impacts. Water levels began to subside at the end of May and returned to Plan 2014 on September 2.

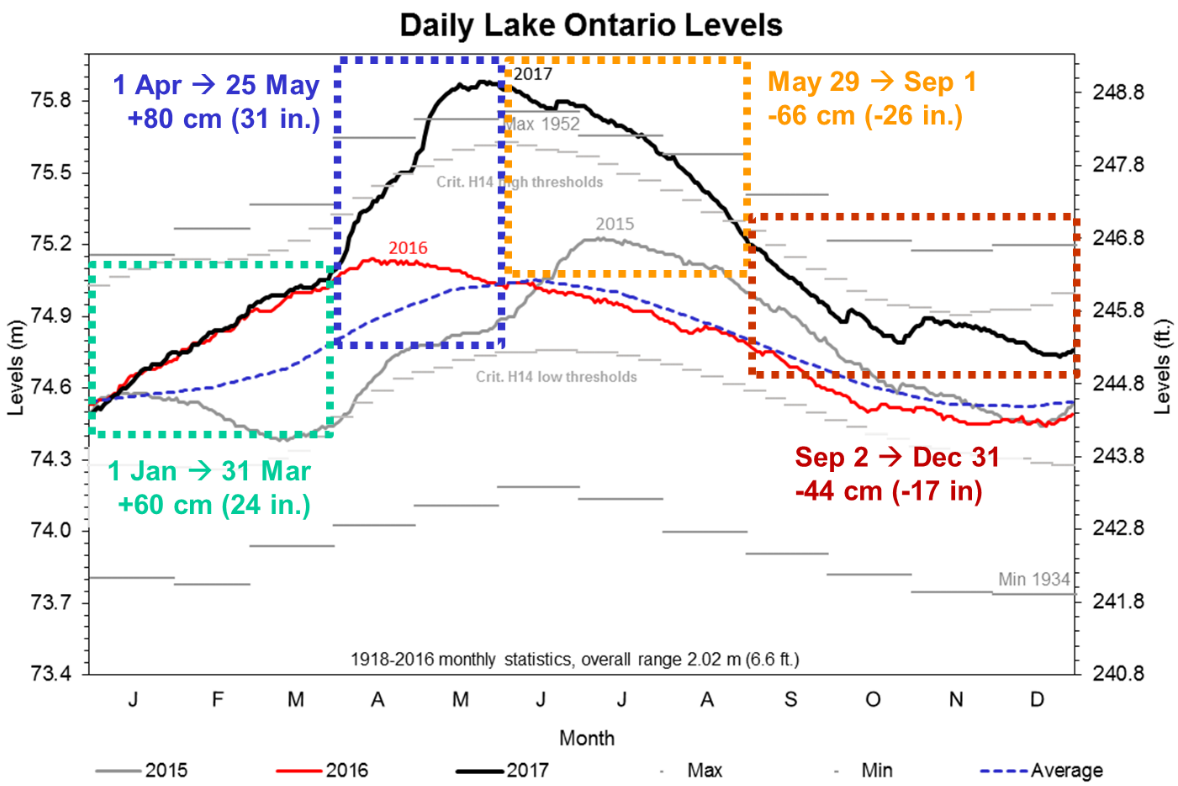


Figure 3.2: Lake Ontario 2017 Water Levels (from ILOSLRB, 2017a)

3.2 Timeline of Events

3.2.1 Initial Conditions

The hydrological conditions at the beginning of the year were unremarkable. Lake Ontario water levels were similar to the two previous years (see Figure 3.2) and Lake Erie, which supplies about 85% of the net inflow to Lake Ontario, was slightly above average but comparable to the two previous years as well. Water levels at Montreal were below average and ice was beginning to form on the St. Lawrence River upstream of Montreal. All conditions suggested that 2017 would be a normal year (ILOSLRB, 2018).

3.2.2 January to March – Variable Winter Temperatures

The St. Lawrence River experienced five freeze-thaw cycles during the first quarter of 2017. The freeze-thaw cycles required the ILOSLRB to reduce outflows from Lake Ontario to reduce the risk of ice jam formation and allow a stable ice cover to form. The I-limit flow is based on engineering calculations of flow rates that allow stable ice to form and reduce the risk of ice jams. The I-limit, which is defined in Plan 2014, is based on how the ILOSLRB operated during similar conditions in the past when it deviated from Plan 1958DD (IJC, 2017). Daily mean temperatures from January to March at Kingston, Cornwall, and Montreal are shown in Figure 3.3.

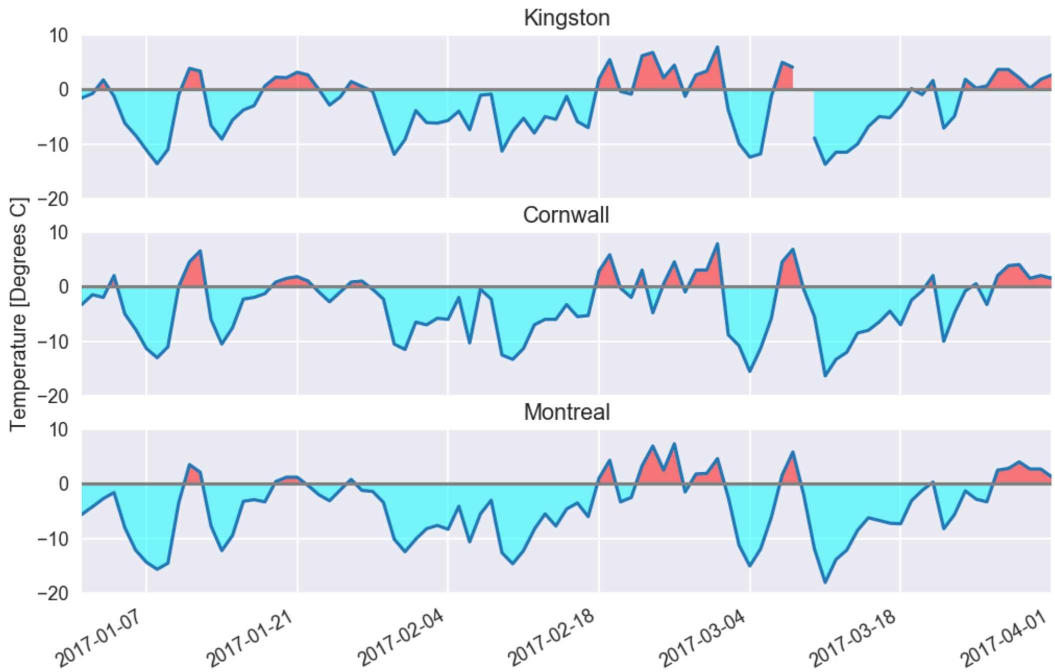


Figure 3.3: Daily Mean Temperatures in Kingston, Cornwall, and Montreal from January to April 2017

As a result of the reduced outflows during the first four months of 2017, water levels in Lake Ontario were above average in the beginning of April. However, water levels were similar to those in 2016 and were well below the maximum recorded for January to March.

3.2.3 April to May – Extreme Wet Weather

April and May saw heavy and persistent rainfall across nearly the entire Lake Ontario-St. Lawrence River basin. New precipitation records were set for January through May at many locations around the basin including: Toronto, Bellville, Ottawa, Montreal, and Rochester. The average precipitation at these five cities was 280 mm for April and May, and 530 mm for January through May (ILOSLRB, 2018). Water levels in Lake Ontario rose rapidly in April as a result of the very high net basin supplies (Figure 3.4).

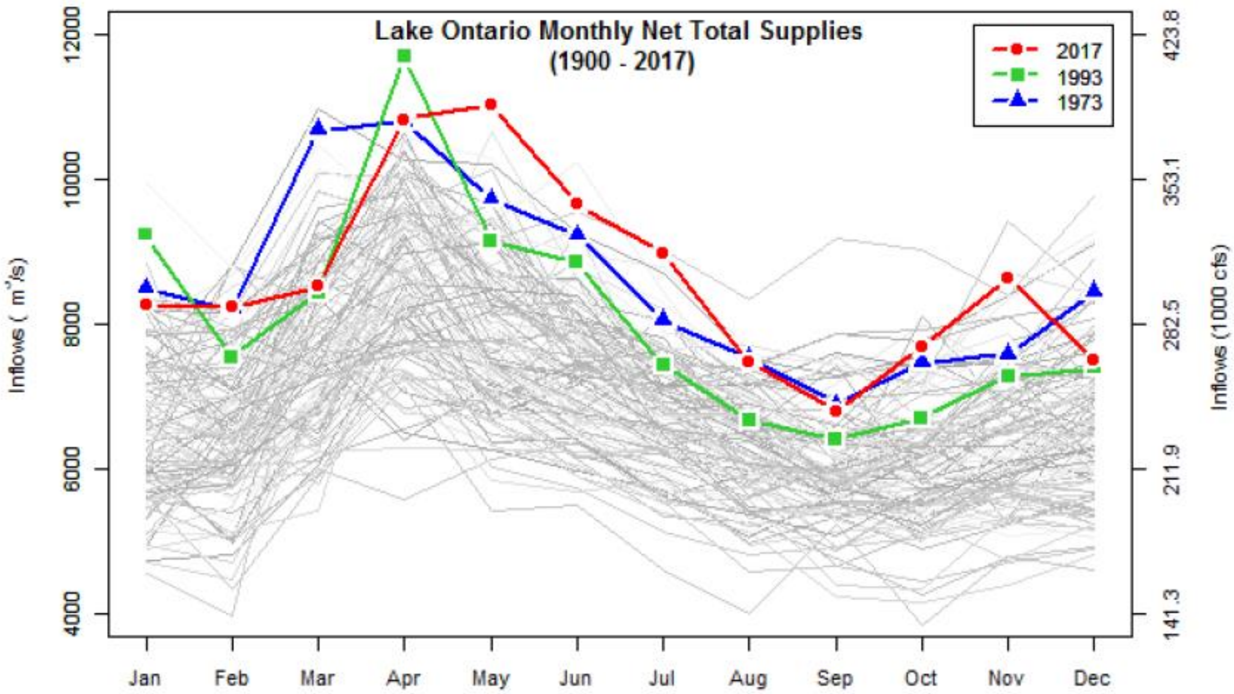


Figure 3.4: Net Total Water Supplies to Lake Ontario (from ILOSLRB, 2018)

Extensive flooding along the Ottawa and St. Lawrence rivers in May 2017 required that outflows from the Moses-Saunders dam in Cornwall be carefully managed to balance upstream and downstream flooding impacts. During this time, water levels in Lake Ontario increased to the highest ever recorded. As flood waters receded downstream, outflows were increased to the highest ever released on a sustained basis.

3.2.4 June to August – Record Outflows Allowing for Safe Navigation

The Plan 2014 L-limits govern the maximum outflows after criterion H14 is exceeded. In June and July 2017, the maximum outflows from Lake Ontario were held at 10,400 m^3/s, which is the “absolute maximum outflow possible to maintain adequate levels and safe velocities for navigation in the International Section of the St. Lawrence River” (Caldwell, 2017c). This deviation was the largest sustained outflow on record.

Water levels began to lower and continued to do so for the rest of the summer. Despite this, water levels remained at record high levels for June and July before falling below the previous monthly records in August. Outflows were reduced to the rule curve limits in mid-August, and by the end of the month water levels dropped below the H14 thresholds. Flows were gradually reduced in August before reaching the H14 thresholds to ensure safe navigation in the St. Lawrence River.

3.2.5 September to December – Return to Plan 2014

Lake Ontario water levels dropped below the 2% exceedance water level for the quarter-month (Criterion H14) in late August. On September 2, outflows were reduced to the Plan 2014 levels and held there until late December when flows were reduced to assist in the formation of a stable ice cover.

3.2.6 Discussion

The first half of 2017 was an extremely wet period for the Lake Ontario and Ottawa River basins. Despite the above-average precipitation in January through March, water levels in Lake Ontario were similar to those in 2016. The extreme precipitation that fell over the majority of the Lake Ontario and Ottawa River basins in April and May could not have been predicted weeks or months into the future.

The response under Plan 2014 would not have been appreciably different under Plan 1958DD. The ILOSLRB adjusted the Lake Ontario outflows about two dozen times in April but were not able to sustain the flows as high as the rule curve limits due to the flooding downstream (F-limit criterion). Higher flow releases would have exacerbated flooding in Montreal and other locations. It wasn't until May 24 that downstream water levels abated, allowing outflows to be increased beyond the rule curve limits (Caldwell, 2017a).

Navigation concerns in the St. Lawrence Seaway governed the maximum outflows in the summer. The ILOSLRB evaluated the additional flood relief possible (by increasing outflows) against the potential impacts of closing the Seaway. It was noted that the Seaway has an economic impact of about $35 billion annually and any interruption in the flow of goods is expected to have immediate and pronounced impacts on the economy of the Great Lakes (GLAM, 2018b).

The conditions that led to the 2017 high water levels could not have been predicted. It is unfortunate that Plan 2014 was implemented in an unusual weather year, as the flooding impacts would not have been appreciably different under Plan 1958DD (+/- 2 cm, see GLAM, 2018a). Both the I-limit and F-limits (which largely characterized ILOSLRB's response in 2017) are explicit rules based on decisions made by the ILOSLRB under similar extreme circumstances in the 1990s.

3.3 Impacts on the Toronto Islands

Toronto Island Park was closed between May 4 and July 30, 2017 (City of Toronto, 2018). Staff from the City of Toronto and TRCA responded to the flooding with emergency mitigation measures such as sandbags and pumps. Ramps and fenders were installed at the Jack Layton Ferry Terminal and at Ward's Island dock to enable the ferries to continue operation during the high water levels.

The closure of Toronto Island Park (along with emergency mitigation measures) cost the City an estimated $8 million, with repair and shoreline remediation work expected to cost another $7 to 8 million (City of Toronto, 2018). The flood impacts include: building and infrastructure damage, business interruption, time off work, additional expenses, and post-flood clean up. The impacts and costs of the 2017 flooding will be developed in the Flood Risk Assessment report.

4. Lake Ontario Return Period Water Levels

Return period water levels for Ontario locations on the Great Lakes were developed by the Ontario Ministry of Natural Resources (OMNR, 1989). The report defines the 100-year flood level, which is the stillwater level (or peak instantaneous water level) having a 1% annual chance of being equalled or exceeded. The stillwater level is equivalent to the hourly water level.

The return period water level estimates in OMNR (1989) were developed for static lake levels (e.g. monthly average levels), storm surge, and all combinations of static lake levels and storm surge. The statistical analyses were conducted using the HYDSTAT software package developed by OMNR (1982). The combined (or joint) probability approach used in OMNR (1989) is appropriate when the period of record is short.

In OMNR (1989), the pre-regulation monthly average lake levels (1900-April 1960) were adjusted to the constant set of conditions existing after 1960 (regulation conditions, diversions, etc.) to form a consistent basis of comparison. Thereafter, an annual maximum series extreme value analysis was conducted using the highest annual monthly mean water levels from 1900 to 1987.

Storm surge (or wind setup) was calculated in OMNR (1989) by subtracting the mean monthly water level from the hourly water level measurements. A computer model was used to estimate storm surges for locations between gauge stations. An annual maximum series extreme value analysis was then conducted using the highest annual surges from 1962 to 1987.

All possible combinations of static water levels and storm surge were then analysed using a combined probability analysis. The stillwater level was taken as the maximum water level resulting from all combinations of static water levels and surges. For example, the 100-year stillwater level is the maximum water level resulting from the 100-year static level and 1-year surge, 50-year static level and 2-year surge, etc.

Note that 0.13 m must be added to the water levels in OMNR (1989) to convert between IGLD55 and IGLD85 datums.

4.1 Static Water Levels

Baird repeated the OMNR (1989) static water level analysis using simulated water levels from Environment Canada under Plan 1958DD for the period from 1900 to April 1960, and measured water levels from April 1960-1987. The analysis was conducted using the HYDSTAT software package and selecting the Log-Pearson Type 3 distribution (which was the best fitting distribution). The results were within 2 cm of the OMNR study.

Baird then updated the static water level return periods for Lake Ontario using the additional 31 years of measured water level data (1988-2018). Considering that the simulated water levels (1900-1960) cover a period of lower water supplies to the Lake Ontario basin, and also that the pre-1960 water levels needed to be adjusted to the conditions existing after the St. Lawrence Seaway was constructed, Baird conducted another extreme value analysis using only the water level data from 1962-2018. This period coincides with the period of hourly water level measurements at the Toronto gauge. This analysis resulted in higher estimates of the return period water levels because water supplies were greater in the post-regulation period, and therefore, is a conservative approach (i.e. errs on the side of higher extreme lake levels). The return period static water level estimates are provided in Table 4.1.

Table 4.1: Lake Ontario Return Period Static Water Levels

Data Range	Return Period Static Water Level (m IGLD85)							
	2 year	5 year	10 year	25 year	50 year	100 year	200 year	500 year
1900-1960 simulated 1960-1987 observed*	75.05	75.23	75.33	75.44	75.52	75.59	75.66	n/a
1900-1960 simulated 1960-2018 observed	75.09	75.27	75.37	75.49	75.57	75.65	75.72	75.82
1962-2018 observed	**75.14**	**75.34**	**75.46**	**75.60**	**75.70**	**75.79**	**75.88**	**75.99**

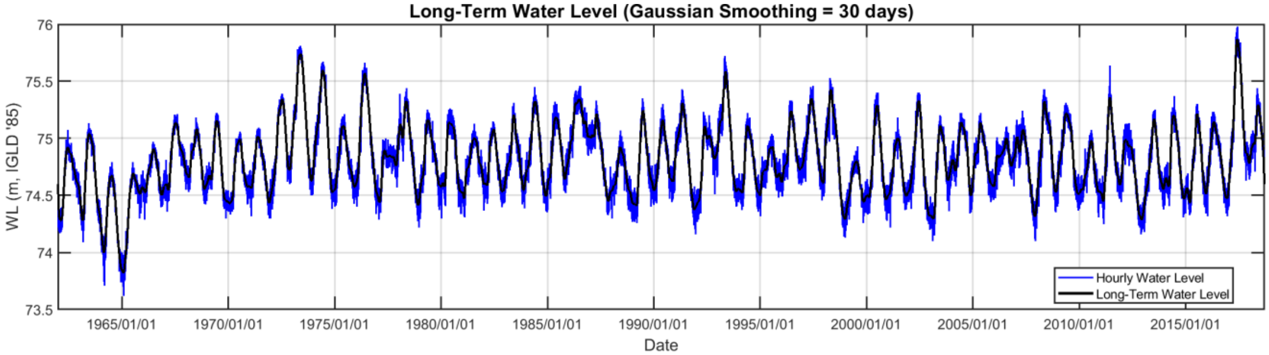
*OMNR (1989) study

It is recommended that the 1962 to 2018 dataset be used to update the return period static water levels. The dataset covers 57 years of water level measurements under regulation conditions similar to the present. The Toronto Islands Shoreline Management Study (Baird,1994) identified issues with the adjustment of pre-regulation water levels used in OMNR (1989) and recommended that recorded monthly data from 1960-1993 be used to develop the return period static water level estimates. The 100-year static water level recommended by the Shoreline Management Study is 75.81 m.

4.2 Surge Levels

Storm surge (wind setup) estimates for Toronto were developed by OMNR (1989) by subtracting the monthly mean water level from the hourly water level measurements. An annual maximum series extreme value analysis was then conducted using the largest surges for each year.

Baird updated the storm surge analysis using the additional 31 years of measured data (1988-2018). In the analysis, static water levels were calculated using a Gaussian-weighted 30-day moving average filter to eliminate the stairstep effect between months. Surge was calculated by subtracting the hourly water level measurements from the “smoothed” static water level (Figure 4.1).



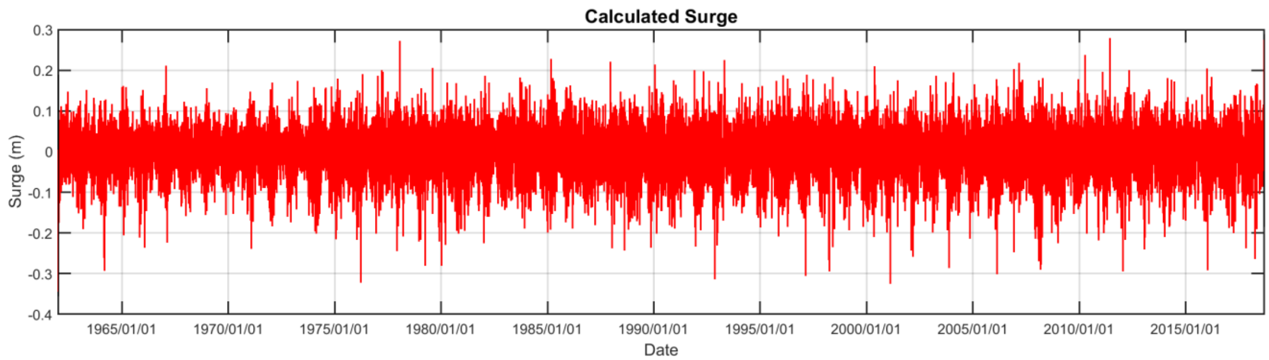


Figure 4.1: Hourly and Static Water Level, and Calculated Surge at Toronto

Considering that surges are driven by independent storm events, a peak-over-threshold analysis was used to identify the largest surge events in the dataset. Using this method, more than one surge event can be identified per year. The largest surge on record was 0.28 m and occurred on June 4, 2011. Surges up to 0.15 m are common.

The HYDSTAT software package was used to estimate the return period surge levels from the 57 largest surges on record. The Log-Pearson Type 3 distribution, which was the best fitting distribution, was selected. The updated return period surge levels for Toronto are summarized in Table 4.2. The surge estimates for the 25-year return period and greater are somewhat smaller than those in OMNR (1989).

Table 4.2: Toronto Harbour Return Period Surge Levels

Data Range	Return Period Surge Level (m)							
	2 year	5 year	10 year	25 year	50 year	100 year	200 year	500 year
1962-1987 observed*	0.16	0.21	0.24	0.28	0.31	0.34	0.37	n/a
1962-2018 observed	0.18	0.20	0.22	0.24	0.26	0.28	0.30	0.34

*OMNR (1989) study

4.3 Return Period Stillwater Levels

The stillwater level is the hourly-averaged water level and includes the effects of wind setup (i.e. surge). The return period stillwater levels were estimated following the combined probability approach used in OMNR (1989) and the annual maximum series approach using hourly water levels. The combined probability approach tends to be slightly more conservative than the maximum series approach as it considers surges occurring at lower static water levels (such as storms occurring in the fall when static water levels are lower).

The HYDSTAT software package was used to estimate the return period stillwater levels using the combined (or joint) probability of different static water level and surge combinations. HYDSTAT was also used to calculate the return period stillwater levels using the annual maximum hourly water levels. The Log-Pearson Type 3 distribution was the best fitting distribution in both cases. The return period stillwater levels from OMNR (1989) and the updated estimates using the two approaches are presented in Table 4.3.

Table 4.3: Toronto Harbour Return Period Stillwater Levels

Type	Return Period Stillwater Level (m IGLD85)							
	2 year	5 year	10 year	25 year	50 year	100 year	200 year	500 year
OMNR (1989) Combined Probability	75.23	75.40	75.49	75.60	75.67	75.74	75.80	n/a
Updated Combined Probability (1962-2018)	**75.33**	**75.53**	**75.65**	**75.79**	**75.89**	**75.98**	**76.07**	**76.18**
Hourly Water Levels (1962-2018)	75.26	75.46	75.59	75.73	75.83	75.92	76.01	76.12

It is recommended that the combined probability analysis using the 1962-2018 dataset be used for the updated stillwater levels. For comparison, the 100-year stillwater level recommended in the Shoreline Management Study is 75.95 m (Baird,1994).

4.4 Influence of Change in Regulation Plans

Plan 2014 was developed to restore wetland ecosystems by increasing the natural variability of Lake Ontario water levels. In particular, the plan endeavours to increase the frequency of moderate high and moderate low water levels that were not experienced under Plan 1958DD. Under extreme weather conditions, outflows from Lake Ontario are governed by safety considerations (ice, flood, and navigation limits) that are unchanged from Plan 1958DD.

The simulated water level time series provided by Environment Canada (personal communication, J. Bruxer,15 February 2018) was used to assess the influence of the change in regulation plans on return period water levels. The simulations were carried out for Plan 1958DD, Plan 2014, and Pre-project conditions using observed inflows and other conditions for 1900-2008. Exceedance curves of the annual maximum monthly water levels for the two regulation plans are shown in Figure 4.2. The steeper slope of the Plan 1958DD exceedance curve indicates that most of the values fall within a narrow range. For example, the moderate highs and moderate lows (values between 20% and 80% exceedance) under Plan 1958DD fall between 75.00 and 75.25 m. The moderate highs and moderate lows under Plan 2014 fall between 74.90 and 75.40 m.

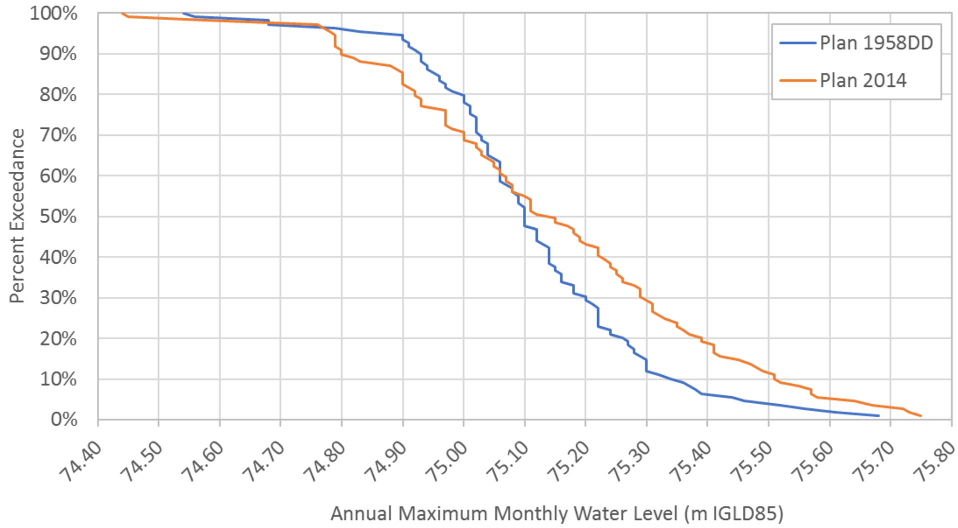


Figure 4.2: Distribution of Simulated Annual Maximum Monthly Water Levels under 1958DD and 2014 Regulation Plans

The simulated annual maximum monthly water level exceedance curves were used to estimate the impact of the change in regulation plans on the return period static water levels (surge estimates are not affected by the change in regulation plans). At the 10% exceedance level, Plan 2014 is expected to result in water levels approximately 0.15 m higher than under Plan 1958DD. At the 1% exceedance level, the difference is 0.07 m. This compares with the 0.06 m difference reported in IJC (2014) for the highest historical supply scenario. The differences in water levels under the two plans are related to how the plans perform before the extreme water levels are reached. As such, it is suspected that the differences between the plans will decrease at supply conditions greater than the historical simulations. However, due to a lack of evidence to support this hypothesis, the 0.07 m difference observed at the 1% exceedance level was extrapolated to the 200- and 500-year return periods. The estimated return period stillwater levels under Plan 2014 are provided in Table 4.4.

Table 4.4: Estimated Toronto Harbour Return Period Stillwater Levels Under 2014 Regulation Plan

Data Range	Return Period Stillwater Level (m)							
	2 year	5 year	10 year	25 year	50 year	100 year	200 year	500 year
Updated Combined Probability (Static + Surge)	75.33	75.53	75.65	75.79	75.89	75.98	76.07	76.18
Plan 2014 difference	0.05	0.12	0.15	0.15	0.12	0.07	0.07	0.07
Estimated Plan 2014 stillwater level	**75.38**	**75.65**	**75.80**	**75.94**	**76.01**	**76.05**	**76.14**	**76.25**

It is recommended that the return period water levels for Toronto Islands be updated to account for the change in regulation plan as described in Table 4.4. The 100-year flood level should be updated to 76.05 m IGLD85.

5. Climate Change Impacts on Water Levels

The Ontario Climate Consortium and Ontario Ministry of Natural Resources and Forestry published a climate change synthesis report for the Great Lakes basin in 2015 (McDermid et al., 2015). The report draws on over 70 water level and surface hydrology studies published since 2010 for the Great Lakes basin. The report outlines the anticipated climate change impacts, evidence, uncertainty, and agreement between studies in language that this accessible to the general public. Findings from the synthesis report will be referred to throughout this section as it reflects the current state of climate change science for the Great Lakes basin.

5.1 Projected Climate Change Impacts

The impacts of climate change on long-term water levels in the Great Lakes are uncertain and are likely to remain uncertain even as climate change science advances. The uncertainty is related to the complexity of modelling the hydrological conditions in the Great Lakes basin including their long-term cyclic nature (precipitation, evapotranspiration, runoff, etc.), and predicting future green house gas levels which will depend on human actions and behaviours.

Future water levels will be most affected by changes in air temperature and precipitation. Over the past 60 years, average annual air temperatures have increased and are predicted to continue increasing. The increase in air temperature is expected to result in lower water levels due increased evapotranspiration. The past 60 years have also been slightly wetter than the historical average and annual precipitation is predicted to increase over the next century. However, the increase in air temperature is predicted to be more significant than the increase in precipitation, resulting in drier conditions and lower lake levels (McDermid et al., 2015).

The natural variability in water supplies is likely more significant than the anticipated climate change impacts on water levels in the Great Lakes. Long-term (decadal) fluctuations in water supplies have been measured since 1860 (see Figure 2.3) and are believed to be driven by large-scale atmospheric and oceanic circulation patterns such as the Atlantic Multidecadal Oscillation (Hanrahan et al., 2014; Watras et al., 2014). These large-scale anomalies affect air temperature, moisture availability, and precipitation. The natural variation in water levels is approximately 2 m for Lake Ontario.

The terms, “confidence” and “uncertainty” are used extensively in climate change literature. In general, confidence relates to the amount, quality, and agreement of the evidence, and uncertainty relates to the magnitude of the unknowns. In McDermid et al. (2015), the various studies were reviewed by a cross-section of climate change researchers and information on each topic were evaluated and ranked as low, medium or high confidence based on the agreement among available studies; type, amount, and quality of the evidence; and limitations of the research.

Uncertainty in future projections is also related to the challenges of predicting future human behaviour related to future green house gas levels (scenario uncertainty), and model imperfection. Climate models use mathematical equations to represent complex processes between the atmosphere, earth surface, and human and natural systems. Model uncertainty is related to our understanding of those systems and the accuracy of the model results.

A summary of projected climate change impacts on factors affecting Lake Ontario water levels are provided in Table 5.1. The various factors are discussed in detail in the following sections.

Table 5.1: Projected Impacts of Climate Change on Lake Ontario Water Levels (adapted from McDermid et al., 2015).

Theme	General Projections	Trend	Confidence
Air Temperature	• 1.5 to 7 °C increase by the 2080s depending on climate scenario model used. • Greater increases in the winter.	Increase	High evidence High agreement
Precipitation	• 20% increase in annual precipitation across the Great Lakes Basin by 2080s under the highest emission scenario. • Increases in rainfall, decreases in snowfall. • Increased spring precipitation, decreased summer precipitation. • More frequent extreme rain events.	Increase	High evidence Medium agreement
Drought	• Increases in frequency and extent of drought.	Increase	Low evidence High agreement
Wind	• Increased wind gust events.	Increase	Low evidence Low agreement
Water Temperature	• 0.9 to 6.7 °C increase in surface water temperature by the 2080s. • 42-90 day increase in ice free season.	Increase	High evidence Low agreement
Water Levels	• Water levels in the Great Lakes naturally fluctuate by up to 1.5m. • Long-term water levels in the Great Lakes peaked in the 1980s and have been decreasing since. • Projections of future lake water levels vary; however, they generally suggest fluctuations around lower mean water levels. • Lower water levels are due to several factors including warmer air temperatures, increased evaporation and evapotranspiration, drought, and changes in precipitation patterns.	Decrease	High evidence Low agreement
Ice	• Projected decreases in ice cover duration, ice thickness, and ice extent. • Increased mid-winter thaws, changing river ice dynamics.	Decrease	Medium evidence High agreement
Flood	• Increases in flood severity and frequency.	Increase	Medium evidence Medium agreement

5.1.1 Air Temperature

There is high confidence that air temperatures in the Great Lakes basin have risen in the past 60 years and will continue to rise in the future. Average annual air temperatures have risen by up to 2°C, and are predicted to continue to rise regardless of the emissions scenario (Lofgren et al., 2002; Hayhoe et al., 2010; McKenney et al., 2011). The largest temperature increases have occurred and are projected to occur in the winter and spring (McKenney et al. 2011), resulting in more winter rainfall (less snowfall), less ice cover (more evaporation), and also affecting the timing of the spring freshet. Higher air temperatures in the summer and fall are projected to result in increased evaporation and plant transpiration (collectively evapotranspiration).

5.1.2 Precipitation

There is medium to high confidence that the Great Lakes basin is in a period of slightly wetter weather. Future projections indicate that annual precipitation will increase by up to 20% across the Great Lakes basin (Lofgren et al., 2002; McKenney et al., 2011).

Rising air temperatures are expected to result in a higher percentage of precipitation falling as rain, and less as snow. Snowfall losses of up to 48% are projected for the Great Lakes basin by the end of the century (Notaro et al., 2014). The projected increase in winter rainfall and decline in snowpack is expected to affect the timing and magnitude of the spring freshet.

Rainfall amounts are projected to increase in the spring and decline in the summer (Kling et al., 2003; Hayhoe et al., 2010). The resulting shifts in the timing of precipitation and snowmelt could present challenges for lake regulation.

Heavy rainfalls are twice as frequent as a century ago and are projected to become more frequent in the future (Changnon and Kunkel, 2006; Kling et al., 2003). Heavy rainfalls are more of a concern for flood-prone urban and riverine areas than the level of Lake Ontario.

5.1.3 Drought

There is moderate confidence that the Great Lakes basin has been and will become more vulnerable to drought (Bonsal et al., 2011). Air temperature and evapotranspiration are projected to increase in the summer while precipitation is predicted to decline.

5.1.4 Wind/Storminess

There is low confidence in projections of future wind speeds and wind patterns. It is believed that warmer air and water temperatures in the Great Lakes may increase atmospheric turbulence, resulting in higher wind speeds in the lower atmosphere (Austin and Colman, 2007; Desai et al., 2009; Huff et al., 2014). However, other studies such as Yao et al. (2012), project a decrease in Lake Ontario wind speeds by the year 2100. Cheng et al. (2012) projected that wind gusts will become at least 10% more frequent by the end of the century.

5.1.5 Water Temperature

There is moderate confidence that surface water temperatures in the Great Lakes basin have risen in the past century and will continue to rise in the future. The high evidence and low agreement for this topic indicates that there is considerable variability between studies. The smallest increases in water temperature are projected for Lake Ontario (Trumpickas et al., 2008, 2009). The increase in water temperature is projected to result in less ice cover (duration and extent), resulting in increased evaporation from the lake surface.

5.1.6 Water Levels

There is moderate confidence that water levels in the Great Lakes peaked in the 1980s, declined, and will continue to decline in the future. However, there is limited agreement on the causes of the decline and likely trends for the near (and medium) term future (McDermind, 2015). Masking the climate change impacts are the much larger natural (decadal) cycles of high and low water supplies.

Projections indicate that future mean water levels will be similar or slightly lower due to higher evapotranspiration rates, and changes is precipitation patterns (Mortsch et al., 2003; Hayhoe et al., 2010; Lofgren et al., 2002; McKenney et al., 2011; Angel and Kunkel, 2010; MacKay and Seglenieks, 2013). Some earlier studies, which predicted more severe water level declines, are believed to have overestimated evapotranspiration rates (Lofgren et al., 2011). Emerging research using an energy balance approach to evapotranspiration suggest that declines, and possibly increases, in water levels will be modest.

5.1.7 Ice

There is moderate to high confidence that ice cover in the Great Lakes is decreasing and that mid-winter thaws are becoming more frequent. A decrease in the duration and extent of the ice cover will result in increased evaporation from the lake surface. The greatest evaporation losses on the Great Lakes occur in the fall and winter when cold, dry air blows over the warmer lakes (Mortsch et al., 2003). Mid-winter thaws may pose challenges for river ice management.

The extent of ice cover on the Great Lakes decreased 71% between 1973 and 2010 (Wang et al., 2012) and the ice cover period decreased by 1 to 2 months over the past century (McDermid et al., 2015).

5.1.8 Flood

There is medium confidence that summer floods will become more frequent and more severe and that spring floods will become less severe in the Great Lakes basin. Spring runoff is projected to decline due to the predicted decrease in snowfall (Notaro et al., 2014; Shaw and Riha, 2011). However, extreme rainfall events are projected to become more frequent in the future. These changes are likely to result in less frequent riverine flooding (smaller freshets), and more frequent urban (pluvial) flooding.

5.2 Role of Adaptive Management

The Great Lakes-St. Lawrence River Adaptive Management (GLAM) Committee was established by the IJC to review, update, and track information on water levels and hydrologic conditions that might influence how regulated outflows will be managed in the future (ILOSLRB, 2018). While it is possible that future conditions may be more extreme than historical conditions, it is likely that IJC will be at the forefront of emerging climate change research as it relates to the hydrology of the Great Lakes basin.

Furthermore, Plan 2014 allows the IJC to deviate significantly from the Bv7 (Plan 2014 mechanistic) rules under extreme water level and water supply situations. Plan 2014 was developed with an allowance for deviations and reformulation if climatic conditions change enough to warrant them (IJC, 2016) – it was not an attempt to account for the projected impacts of climate change on water levels in the next 80 years. In this spirit, the incorporation of climate change impacts into adaptive planning and management is emphasized while the incorporation into present design water levels is not.

5.3 Summary

The latest climate change research related to precipitation, evaporation, snow and ice cover, and storminess in the Lake Ontario basin were reviewed to estimate potential future changes to static water levels, storm surge, and waves at Toronto Islands.

Over the past 60 years, the Great Lakes basin has become warmer and has been slightly wetter (than the long-term average). Air temperature and precipitation are projected to increase in the future, with water levels in the Great Lakes remaining similar or slightly decreasing (McDermid et al., 2015). The uncertainty in water level projections is related to the relative roles of evapotranspiration and precipitation.

Snowfall and ice cover in the Great Lakes-St. Lawrence River basin are projected to decrease resulting in an earlier and smaller spring freshet (Kling et al., 2003) and increased evaporation from the lake surface in the winter.

Wind gusts, although expected to increase slightly over the next century, are not anticipated to have a large impact on storm surge and waves at Toronto Islands. Storm surge is relatively low at Toronto due to its location on Lake Ontario.

It is likely that the impacts of climate change on static water levels will be less than the natural variability of Lake Ontario and will be manageable within the current regulation plan. If the hydrological conditions of the Great Lakes basin change slowly over time, it is likely that the International Joint Commission's Great Lakes-St. Lawrence River Adaptive Management Committee will be able to evaluate these changes and make recommendations on how to adapt the plan to the changing conditions.

6. Wave Conditions

6.1 Offshore Wave Climate

Offshore wave conditions at Toronto Islands were extracted from Baird's Lake Ontario wave hindcast model. The model was originally developed for the IJC Lake Ontario Wave Climate – St. Lawrence River Water Level Regulation Study (Baird, 2003), and was extended by Baird to support other projects. The hindcast uses the second-generation WAVAD spectral wave model and is based on 50 years of wind and wave data covering the period from 1961 to 2010. The model results were validated against two multi-year sets of wave buoy measurements, as well as data from various shorter-term buoy deployments. It is a standard wave data set used on Lake Ontario.

The offshore hindcast consists of an hourly time series of modelled wave height, period, and direction at a location offshore of Toronto Islands where the waves are unaffected by the water depth. A histogram of wave heights by direction, known as a wave height rose, is shown in Figure 6.1. In general, the offshore wave climate is dominated by waves from the east and southwest.

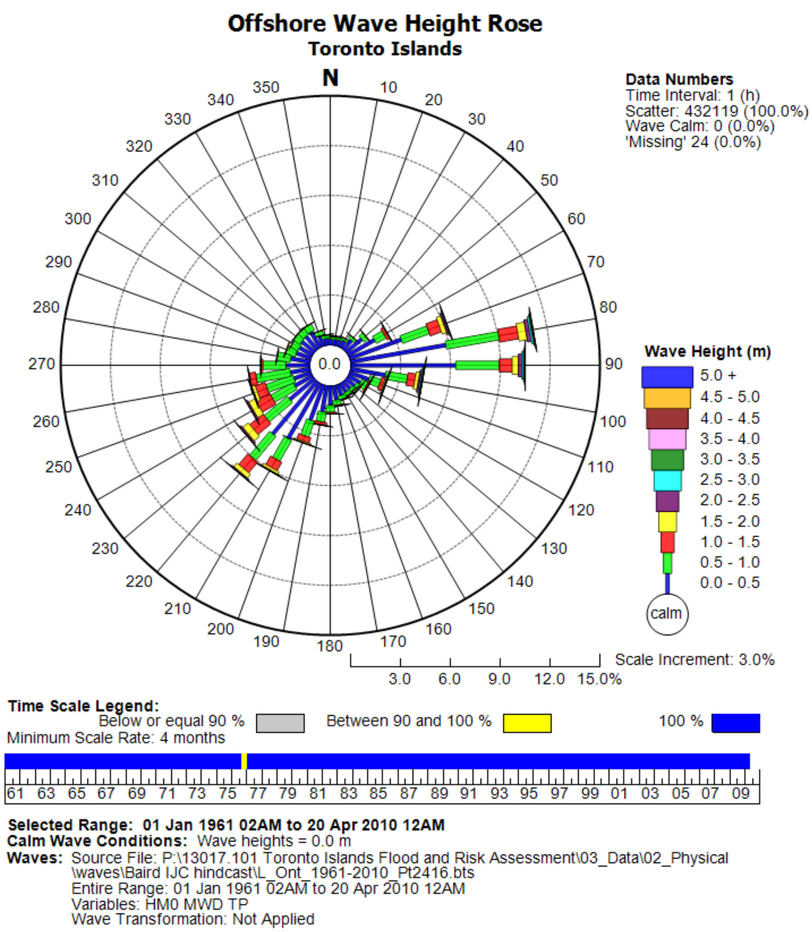


Figure 6.1: Offshore Wave Height Rose at Toronto Islands

The joint distribution of wave height and direction, shown in Table 5.2, indicates that the largest waves come from the east with wave heights up to 5.8 m.

Table 6.1: Offshore Wave Height by Direction for Toronto Islands

Toronto Islands Offshore Wave Climate

Wave Distribution By Height And Direction
Date Range: 01 Jan 1961 02AM to 20 Apr 2010 12AM
Season: All

Direction	Wave Height (m) 0.00-0.50	0.50-1.00	1.00-1.50	1.50-2.00	2.00-2.50	2.50-3.00	3.00-3.50	3.50-4.00	4.00-4.50	4.50-5.00	5.00+	Total	C(%)	Maximum Height (m)
0.00	0.83	0.35	0.02	0.00								1.21	100.00	1.88
22.50	0.88	0.30	0.02	0.00								1.20	98.79	1.63
45.00	2.35	0.56	0.04	0.00								2.96	97.59	1.75
67.50	6.95	3.42	1.33	0.49	0.19	0.09	0.04	0.01	0.00	0.00		12.51	94.63	4.55
90.00	11.67	5.73	1.85	0.85	0.45	0.23	0.13	0.05	0.02	0.00	0.00	20.99	82.11	5.80
112.50	2.49	1.39	0.39	0.12	0.06	0.03	0.01	0.01	0.00	0.00	0.00	4.50	61.12	5.29
135.00	1.43	0.55	0.09	0.01	0.00	0.00						2.08	56.62	2.56
157.50	1.50	0.51	0.09	0.01	0.00	0.00						2.11	54.54	2.91
180.00	2.81	0.99	0.22	0.03	0.00	0.00						4.06	52.43	2.62
202.50	6.17	2.46	0.91	0.23	0.05	0.00	0.00	0.00	0.00			9.82	48.37	4.36
225.00	6.86	4.18	2.14	0.82	0.20	0.04	0.00	0.00	0.00		0.00	14.25	38.55	5.35
247.50	2.49	3.85	1.59	0.54	0.13	0.02	0.00					8.62	24.29	3.19
270.00	3.05	3.14	0.29	0.02	0.00							6.50	15.67	2.12
292.50	2.08	1.25	0.04	0.00								3.37	9.18	1.52
315.00	2.35	1.02	0.03	0.00								3.40	5.80	1.61
337.50	1.70	0.67	0.03	0.00								2.40	2.40	1.74
Totals	55.62	30.39	9.08	3.13	1.08	0.40	0.19	0.07	0.03	0.00	0.01	100.00		
C(%)	100.00	44.38	13.99	4.91	1.78	0.70	0.30	0.11	0.04	0.01	0.01			

Meta Data

0.00% Calm Conditions (Wave Height<0.00 m and Wave Period<0.00 s)

Number of records this selection:	432119		
Total records used in selected interval (including calms):	432119		
Missing data (not included in calculation):	24		
Variables: HM0 MWD TP			
Wave height (all data):	Max: 5.80	Min: 0.02	Mean: 0.57
Wave height (scatter only):	Max: 5.80	Min: 0.02	Mean: 0.57

Legend

Row and column percentages have the following meanings:
Total – based on number of records used in selected interval
C – percent exceedance derived from 'Total'
Frequencies of occurrence are reported in 'percentage'

6.2 Nearshore Wave Transformation

The Danish Hydraulics Institute's MIKE21 Spectral Wave model was used to transform the offshore wave climate to the nearshore region. The computational mesh and model bathymetry are shown in Figure 6.2. The model bathymetry was derived from bathymetric survey data collected by TRCA in 2009 and NOAA's GEODAS bathymetric dataset for Lake Ontario.

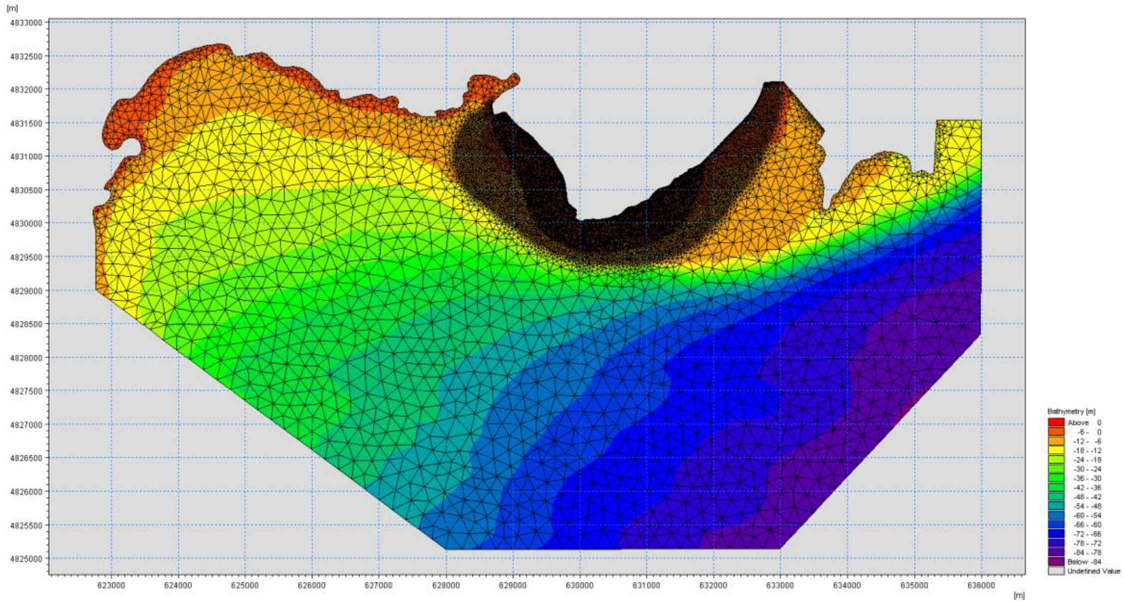


Figure 6.2: Computational Mesh and Bathymetry of Nearshore Wave Model

The nearshore wave model was used to develop wave shoaling and wave refraction coefficients at the nearshore output locations for the range of wave heights, periods, and directions observed at the offshore location. The wave shoaling and refraction coefficients were then used to transform the 50-year hourly time series of offshore wave heights, periods and directions to the seven nearshore output points at a water depth of 8 m (Figure 6.3).

Figure 6.3: Offshore and Nearshore Model Output Locations

6.3 Toronto Islands Return Period Wave Heights

A peak-over-threshold extreme value analysis was used to estimate return period wave heights at the offshore and nearshore output locations (see Table 6.2). Nearshore wave conditions vary along the perimeter of the islands due to differences in bathymetry and sheltering. Points 1 and 2 are partially sheltered by Tommy Thompson Park to the east of the islands and wave heights are smaller. Points 3, 4 and 5 are exposed to long fetches from the east and southwest and experience the largest waves. Points 6 and 7 are sheltered by Toronto Islands for waves from the east.

Table 6.2: Toronto Islands Return Period Significant Wave Heights

Location	Return Period Significant Wave Height (m)							
	2 year	5 year	10 year	25 year	50 year	100 year	200 year	500 year
Offshore	4.1	4.6	5.0	5.4	5.6	5.9	6.1	6.5
Point 1	1.8	2.0	2.1	2.3	2.4	2.5	2.6	2.8
Point 2	2.0	2.3	2.4	2.5	2.7	2.9	3.0	3.1
Point 3	2.8	3.1	3.3	3.6	3.8	3.9	4.1	4.4
Point 4	2.2	2.5	2.8	3.1	3.4	3.7	4.0	4.3
Point 5	2.3	2.6	2.8	3.2	3.5	3.7	4.0	4.4
Point 6	2.3	2.5	2.8	3.0	3.2	3.4	3.6	3.9
Point 7	2.1	2.4	2.6	2.9	3.1	3.3	3.4	3.7

6.4 Toronto Inner Harbour Return Period Wave Heights

Waves impacting the northern shore of Toronto Islands are generated from winds blowing across the Toronto Inner Harbour. Due to the relatively short distances across the harbour, wave heights are said to be “fetch limited.” This means that waves will reach a fully-developed state within a short period of time (less than an hour for Toronto Inner Harbour), and that wave heights depend solely on the wind speed and open water fetch distance.

Return period wave heights within the Inner Harbour were estimated by conducting an extreme value analysis of wind speeds at Toronto Island Airport and using empirical wave hindcasting methods to estimate the corresponding wave heights. Wave heights were calculated according to the Shore Protection Manual (USACE, 1977) using the extreme wind speeds, a fetch of 3 km, and a water depth of 8 m. The return period wind speeds and wave heights are summarized in Table 6.3. The results indicate that waves within the Inner Harbour are relatively small, with a 100-year wave height of 1.4 m. These estimates are conservative as they assume extreme wind speeds are approaching from the direction that will give the largest possible fetch length.

Table 6.3: Toronto Inner Harbour Return Period Wind Speeds and Significant Wave Heights

Return Period	2 year	5 year	10 year	25 year	50 year	100 year	200 year	500 year
Wind Speed (km/h)	69	76	83	92	100	108	116	128
Significant Wave Height (m)	0.8	0.9	1.0	1.2	1.3	1.4	1.5	1.7
Wave Period (s)	3.3	3.5	3.7	3.9	4.0	4.2	4.4	4.6

6.5 April 2018 Windstorm

The April 15-16, 2018 windstorm caused widespread damage throughout the Greater Toronto Area. The storm brought freezing rain and high winds which downed trees and power lines. Wind speeds of up to 75 km/hour were recorded at Toronto Island Airport.

Baird updated and extended its Lake Ontario wave hindcast to understand the relative magnitude of the April 2018 storm compared to historical storm events. Fully updating and validating the wave hindcast model is a comprehensive task that is beyond the scope of this study. The updated model was run with high-resolution modelled winds from the Climate Forecast System Reanalysis project from the National Centers for Environmental Prediction. The previous Baird Lake Ontario hindcast used measured winds from land stations on the coast of Lake Ontario and wave buoys in the lake. While the hindcast models performed very similarly at the wave buoys in the lake, differences were noted at the output location near Toronto Islands. The likely cause of the differences is due to air and water temperatures which have not yet been incorporated into the updated model. Differences in air and water temperature affect the transfer of energy between the air and water surface.

Considering this, the predicted wave heights from the April 2018 windstorm were adjusted (upwards) using measured air temperatures at Toronto Island Airport and measured water temperatures in Lake Ontario (data from the wave buoys when they were deployed later that month). The estimated offshore wave height from the April 2018 storm was approximately 5.6 m at Toronto Islands. This places the April 2018 storm somewhere within the top five offshore wave events since 1961 (see Table 6.4). Measured wind speeds at Toronto Island Airport on April 15 and 16 were approximately equal to the 5-year return period wind speed.

Table 6.4: Largest Storms Offshore of Toronto Islands (1961-2010)

Rank	Date	Significant Wave Height (m)	Peak Wave Period (s)	Wave Direction (degrees)	Storm Duration (hours)
1	1985-03-04	5.8	8.9	88	17
2	1965-01-23	5.7	8.9	93	26
3	1977-01-10	5.7	8.9	101	15
4	1999-01-14	5.4	8.9	88	23
5	1986-02-07	4.9	8.9	92	34

6.6 Toronto Islands Shore Protection Structures

A structural assessment of the shore protection structures at Toronto Islands was completed for the Shoreline Management Study (Baird & Reindeers, 1994b). The Centre Island concrete seawall and Algonquin Island steel sheet pile seawall were in good condition at the time of the assessment. The Ward's Island seawall along Cibola Ave from the ferry dock to the Algonquin Island bridge was in fair condition. The Ward's Island seawall along Bayview Ave was in poor condition in 1994 (Baird & Reindeers, 1994b) and is now fronted by a stone revetment. The structures were not inspected as part of this study. Cross-section drawings of the seawalls are provided in Figure 6.4 to Figure 6.6.

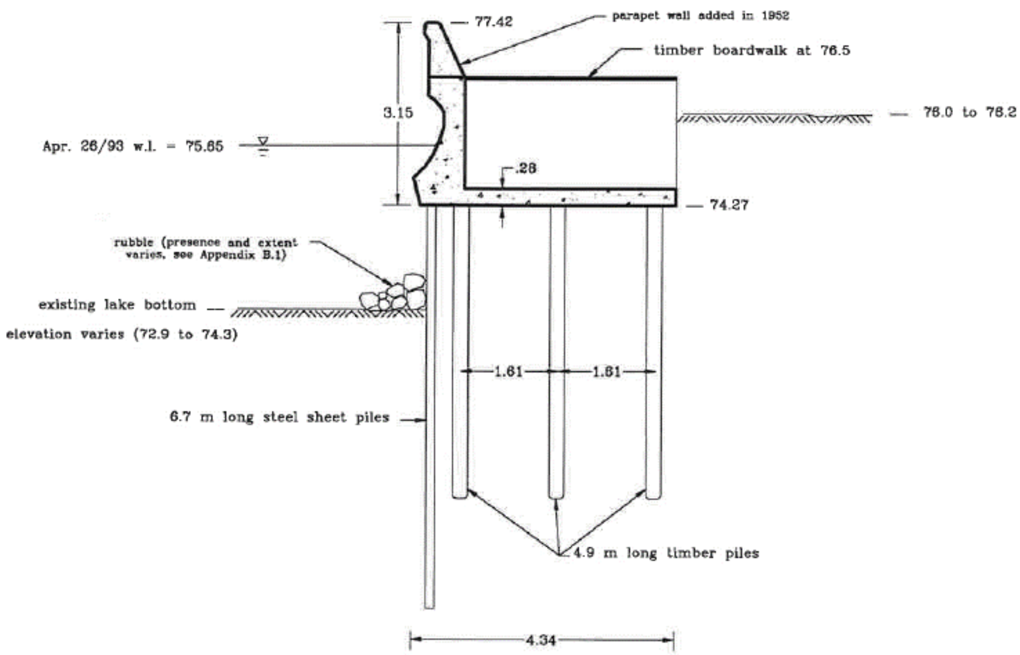


Figure 6.4: Centre Island Seawall Cross-section (from Baird & Reindeers, 1994b)

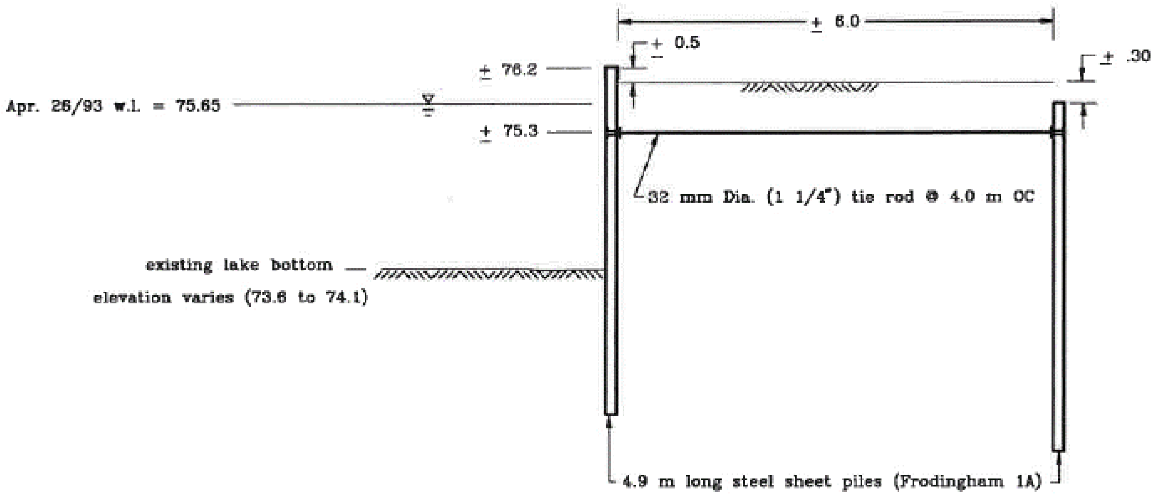


Figure 6.5: Algonquin Island Seawall Cross-section (from Baird & Reindeers, 1994b)

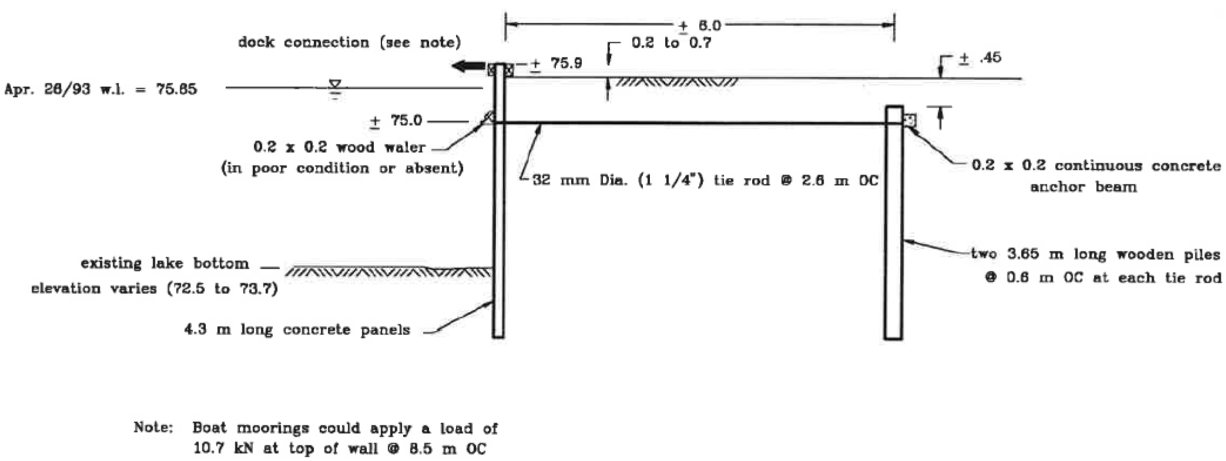


Figure 6.6: Ward's Island Cibola Ave Seawall Cross-section (from Baird & Reindeers, 1994b)

6.7 Wave Overtopping

Wave overtopping was estimated in this study to delineate areas on the Flood Response Maps that could be flooded due to wave overtopping. A definition sketch of wave overtopping is shown in Figure 6.7. The inland extent of wave overtopping is related to the height of the wave bore.

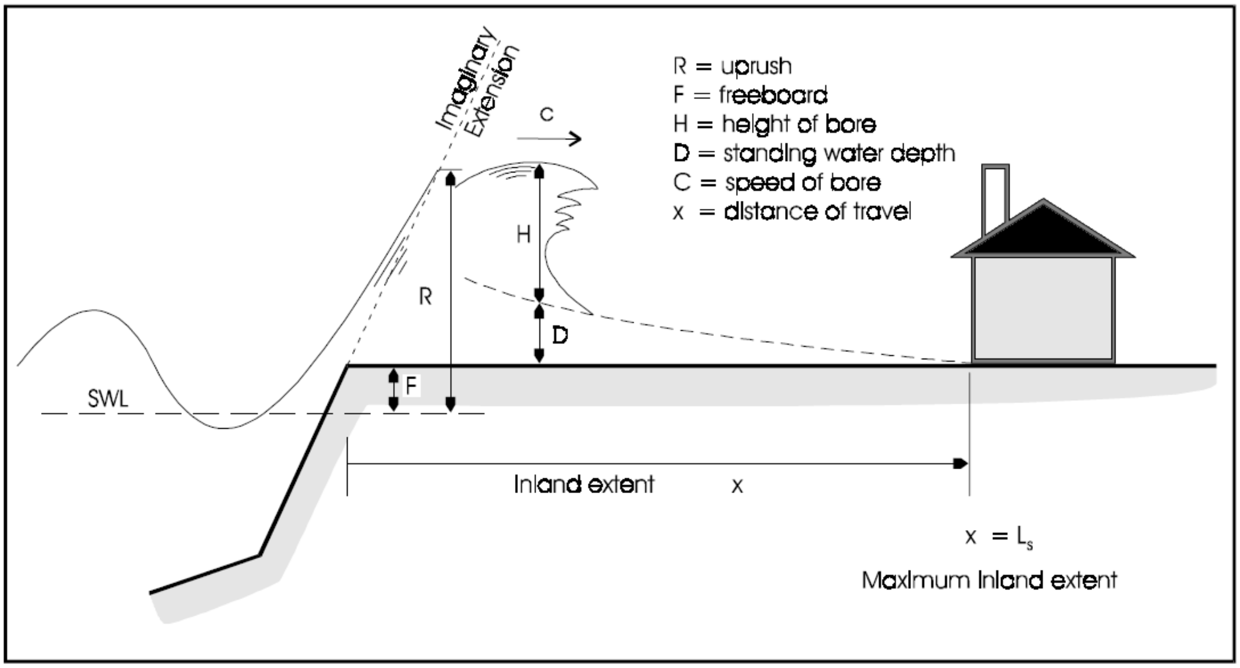


Figure 6.7: Wave Overtopping Definition Sketch (from OMNR, 1996)

Wave overtopping was estimated using an in-house empirical model based on the EurOtop (2016) overtopping manual, Cox and Machemehl (1986), and FEMA (2005). The model calculates the wave runup elevation, volume of overtopping water, inland propagation distance, and depth and velocity of overtopping waves for complex shoreline profiles. The model utilizes a decision tree system to select the appropriate EurOtop equations based on the structure type, profile geometry, water level, and wave conditions.

Wave overtopping was estimated at the three seawalls for wave and water level combinations with a combined probability of 100 years. The simulated events were the: 2-year stillwater level and 50-year wave height; 10-year stillwater level and 10-year wave height; and, 50-year stillwater level and 2-year wave height.

Impulsive wave breaking conditions were predicted at the Centre Island seawall for the simulated events. The waves were predicted to break before or at the seawall, creating an up-rushing jet of water that would splash over the wall. Overtopping volumes and inland distances were observed to increase at higher water levels. A physical model study of the Centre Island seawall by Baird (1994) had wave overtopping rates of 10-70 l/s/m for the 100-year event with overtopping distances of approximately 4 m.

Non-breaking wave conditions were predicted at the Inner Harbour seawalls for the simulated events. The non-breaking waves are predicted to run up and over the wall resulting in “green water” overtopping. The percent of overtopping waves and overtopping volumes were estimated to increase at higher water levels while the inland distance was found to depend on the crest elevation of the wall.

The results of the wave overtopping analysis are provided in Table 6.5. The findings from the analyses are consistent with the Shoreline Management Study (Baird & Reindeers, 1994a), which recommended at 15 m horizontal setback from the Centre Island seawall, and 5 m horizontal setback from the 100-year flood elevation contour for the Inner Harbour shoreline.

Table 6.5: Estimated Wave Overtopping at 100-year Return Period Conditions

Location	Crest Elevation (m)	Type of Overtopping	Percent Overtopping Waves	Overtopping Rate (l/s/m)	Inland Extent of Overtopping (m)
Centre Island Seawall	77.42	Splash	74-100%	20-60	6
Algonquin Island Seawall	76.2	Green water	62-93%	70-80	2
Ward's Island Seawall Cibola Ave (Ferry to Bridge)	75.9	Green water	60-100%	30-120	5

The two types of wave overtopping predicted at the Toronto Island seawalls are shown in Figure 6.8. Green water overtopping occurs when the water depth is relatively deep and the seawall crest is low compared to the water level and wave conditions. Splash overtopping occurs when the water depth is relatively shallow and waves break on or before the seawall creating a violent upward jet of water.

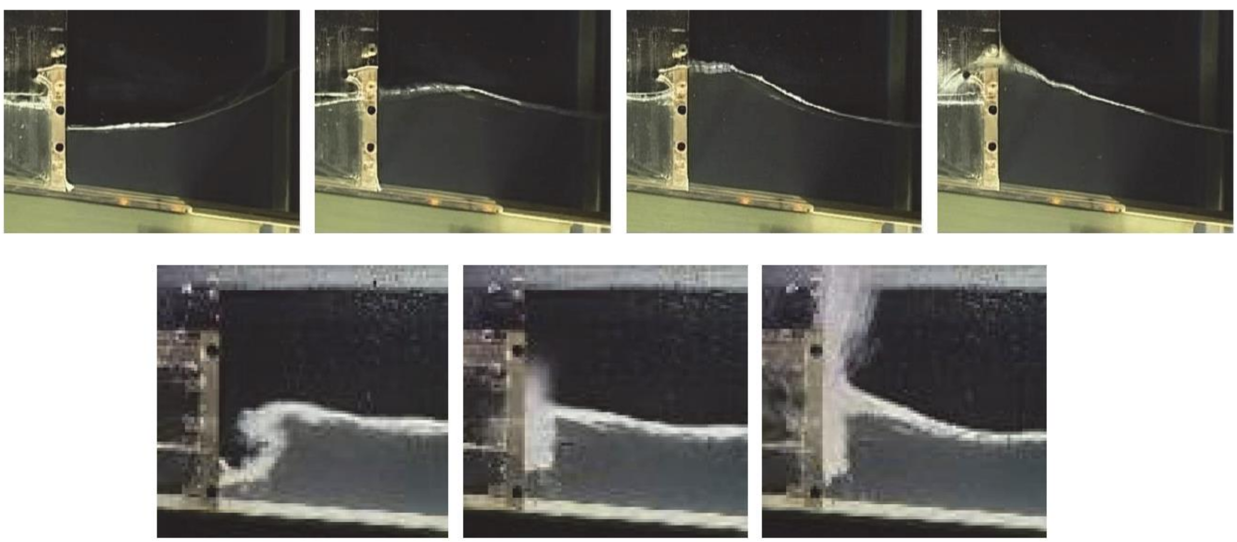


Figure 6.8: Green Water Overtopping (top panel) and Splash Overtopping (bottom panel) at a Vertical Wall (from EurOtop, 2016).

7. Conclusions and Recommendations

The 2017 high water levels were the result of extreme wet weather in the Lake Ontario basin, record inflows from Lake Erie, and reduced outflow capacity due to downstream flooding on the St. Lawrence and Ottawa rivers. The extreme precipitation could not have been predicted weeks or months into the future. Had ILOSLRB been operating under Plan 1958DD instead of Plan 2014, the water level in Lake Ontario would have peaked within +/- 2 cm of the actual peak in June 2017 (GLAM, 2018a).

Return period water levels developed by the Ontario Ministry of Natural Resources (OMNR, 1989) were reviewed and updated using the last 57 years of measured water level data (1962-2018). **The analysis indicates that the 100-year flood level for Toronto Islands, which is defined as the 100-year stillwater level, should be updated to 76.05 m IGLD85.** The recommended 100-year flood level includes a seven-centimeter allowance to account for the change in regulation plans. The Toronto Islands Shoreline Management Study (Baird & Reindeers, 1994a) recommended that the 100-year flood level for Toronto be increased to 75.95 m IGLD85. The highest hourly water level recorded at the Toronto Harbour gauge is 75.98 m IGLD85 (June 4, 2017).

The latest climate change research related to precipitation, evaporation, snow and ice cover, and storminess in the Lake Ontario basin were reviewed to estimate potential future changes to static water levels, storm surge, and waves at Toronto Islands. Current research suggests that water levels in the Great Lakes will remain similar or decline slightly due to increased evapotranspiration. The anticipated impacts of climate change on static water levels are less than the natural variability of long-term lake levels, and will likely be manageable within the current regulation plan. Furthermore, the International Joint Commission's Great Lakes-St. Lawrence River Adaptive Management Committee will review, update, and track information on water levels and hydrologic conditions that might influence how outflows from Lake Ontario will be managed in the future. Therefore, at this time we do not recommend any increase or decrease in the 100-year static water level due to climate change.

There is low confidence in future projections of how wind speeds and wind patterns might be affected by climate change. Future increases in wind speed could result in larger waves and storm surges in Lake Ontario. Storm surge at Toronto is low compared to other locations on the Great Lakes.

Baird's Lake Ontario wave hindcast (1961-2010) was used to evaluate offshore and nearshore wave conditions at Toronto Islands. Wave runup, overtopping, and inland excursion of overtopping waves were calculated for the 100-year event using the combined probability of different combinations of return period waves and stillwater levels. The results of the wave uprush analysis are similar to the Shoreline Management Study (Baird & Reindeers, 1994a), which recommended a 5 m horizontal setback (from the 100-year flood elevation contour) along the Inner Harbour, and a 15 m horizontal setback from the Centre Island seawall.

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Appendix A

Benchmark Information

STATION: 0011959U9526

Also known as:	00159U9526, 59U9526, TORO 1-1959
Monument status:	Existing
Toronto status:	1
Monument type:	BM
Station type:	SPIR

Horizontal datum:	TOR_H-1974
Horizontal accuracy:	UNCLASSIFIED
Latitude:	N43°38′22.4xxxx″
Longitude:	W79°22′51.3xxxx″
Ellipsoidal elevation:	76.xxx
Ellipsoidal elevation order:	Unclassified
UTM-17 Easting:	E630596.xxx
UTM-17 Northing:	N4832898.xxx
UTM-17 Cmbd sc-fact:	0.99979786
UTM-17 Mrdnl convg:	1°07′03.1″
MTM-10 Easting:	E314408.xxx
MTM-10 Northing:	N4833081.xxx
MTM-10 Cmbd sc-fact:	0.99988921
MTM-10 Mrdnl convg:	0°04′55.9″

Vertical datum:	CGVD2013
Vertical accuracy:	First order
Orthometric elev:	75.943
Meridional defl:	
Prime vert defl:	
Undulation:	
Vertical datum:	CGVD-1928:1978
Vertical accuracy:	First order
Orthometric elev:	76.355
Meridional defl:	
Prime vert defl:	
Undulation:	
Vertical datum:	CGVD-1928:PRE-1978
Vertical accuracy:	Tor third order
Orthometric elev:	76.484
Meridional defl:	
Prime vert defl:	
Undulation:	

Location:	Created on 2010/10/10. City of Toronto - Circular GAUGEHOUSE, IN TORONTO HARBOUR, AT SOUTH SIDE OF QUEEN'S QUAY, 8.23 M W OF former alignment of CENTRE LINE OF YORK ST., TABLET IN TOP OF WEST COR OF CONC BASE. FORMER NAME: TORO 1-1959
Maintenance:	Established by Canadian Hydrographic Service 1959. Inspected 2007/10/11. Visible on July 2011 Google StreetView.
Other horiz data [ord]:	NAD-1983:ORIG [-]

(Reference sketch for 0011959U9526 is not available.)

Government of Canada Gouvernement du Canada

Canada

Fisheries and Oceans Canada

Station Benchmarks - Public access

Requests for data, data products and additional information may be made online by completing the Data Request Form.

Benchmarks for TORONTO, ONTARIO (#13320)

Field Descriptions
Expand All

Benchmark Number: 578F Unique Number: 54U578F
Benchmark Number: 579-F Unique Number: 54U579F
Benchmark Number: 86 - 1 Unique Number: 86U9463
Benchmark Number: BENCH PLATE Unique Number: 54U008
Benchmark Number: M053003 Unique Number: M053003
Benchmark Number: MMCCCLXIV Unique Number: 21U2364
Benchmark Number: TORO 1-1959 Unique Number: 59U9526

Benchmark Number: TORO 1-1959
Unique Number: 59U9526
Station Number: 13320
Station Name: TORONTO, ONTARIO

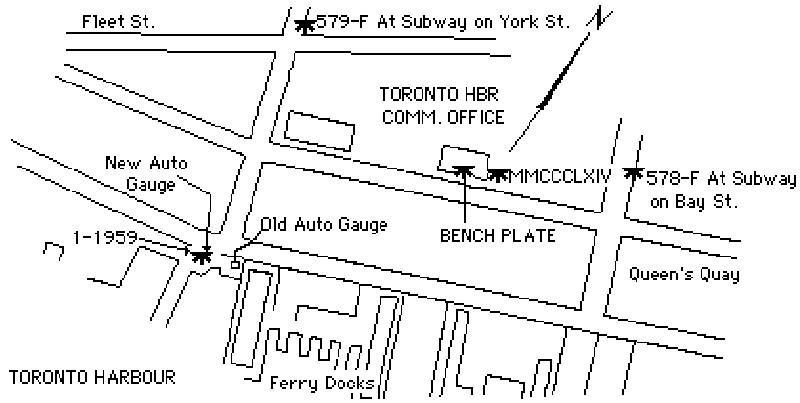
Latitude: 43.64 ° N
Longitude: 79.38 ° W
Established: 1959
Benchmark Condition: Not Known
Setting: VERTICAL
Type: Permanent Agency Marker
Agency: CHS
Last Inspected: 9999

Holding Benchmark	Datum Name	Elevation (metres)	Status
NO	CDIGLD1985	2.205	ACTIVE
NO	IGLD85	76.439	ACTIVE

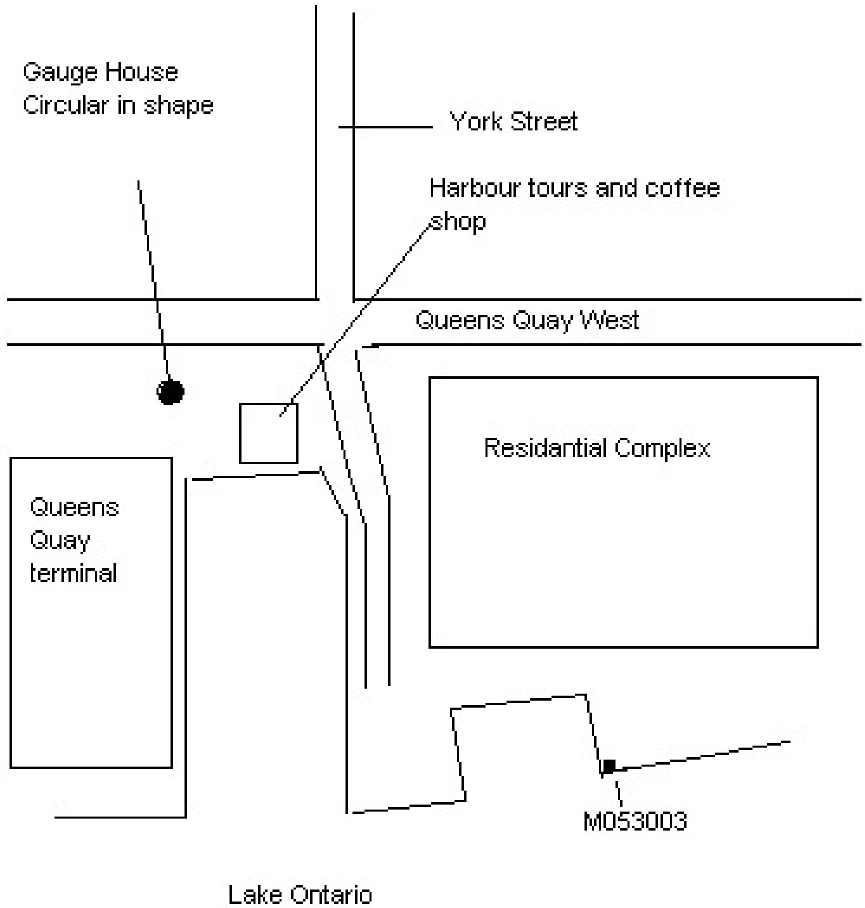
Description:
A C.H.S. bronze tablet stamped TORO 1-1959 set vertically in west corner of concrete base of new gauge location, at the intersection of York Street and Queen's Quay, at the foot of York Street. Horizontal Position updated to NAD83CSRS in January 2010.

Station Sketch

Sketch Status: ACTIVE



Sketch Status: ACTIVE



Date Modified: 2015-06-19