CSCE Annual Conference
*Growing with youth – Croître avec les jeunes*

Laval (Greater Montreal)
June 12 - 15, 2019

# ASSESSING POTENTIAL CLIMATE CHANGE IMPACTS TO A STORMWATER MANAGEMENT SYSTEM FOR A RESIDENTIAL SUBDIVISION IN SOUTHERN ONTARIO

Senior, M.[1,5], Scheckenberger, R. [2], Nimmrichter, P. [3], Ingebrigsten, M. [4]
[1] Wood Environment & Infrastructure Solutions, Canada
[2] Wood Environment & Infrastructure Solutions, Canada
[3] Wood Environment & Infrastructure Solutions, Canada
[4] City of Welland, Canada
[5] matt.senior@woodplc.com

**Abstract:** Numerous previous studies have concluded that climate change has the potential to increase rainfall (depth, peak intensity, and frequency). These changes have the potential to impact the performance of stormwater management (SWM) systems which were designed and constructed based on long-term rainfall datasets from historic records, which inherently assume stationarity and do not account for climate change. Changes to rainfall severity may as a result cause decreased SWM system performance, leading to increases in flooding and adverse impacts to downstream receivers. The City of Welland, Ontario has been proactively considering and planning for the impacts of climate change through the completion of several vulnerability assessments and reviews of design standards. In order to better understand the potential influences of climate change on system performance, a focused assessment of climate change impacts was undertaken for the 22-hectare South Pelham Subdivision. An integrated, dual-drainage hydrologic/hydraulic model was developed, including storm sewers, roadways, and the downstream SWM facility. The modelling was applied to assess a range of climate-change altered rainfall scenarios, and to quantify the range of potential impacts to the performance of the storm sewer system, overland drainage (roadways), SWM facility, and downstream receivers. In addition, the implications to the design of these features, if designed to climate-changed altered rainfall scenarios, were considered and assessed, including the cost implications associated with building climate resiliency into the system. The results of these combined analyses provide a greater insight into the potential climate change impacts to SWM systems, both to designers and municipalities.

## 1 INTRODUCTION AND PROBLEM STATEMENT

Stormwater Management refers to the broad suite of measures to collect, convey, treat, and control stormwater runoff, typically implemented in the process of re-developing land or implementing infrastructure works. For measures which require conveyance (storm sewer, channel, and overland flow design) or control (quantity control measures such as end-of-pipe SWM facilities or “ponds”), design requirements are typically defined by municipal design criteria or guidelines. These guidelines typically refer to a 1 in ‘n’ year storm event, where ‘n’ refers to the average return period of the rainfall parameter in question (i.e. a storm of this intensity would occur, on average in a given location once in every n years). In Canada, these estimates of return period/frequency are most commonly sourced from Environment Canada, which operates and maintains long-term rainfall and precipitation monitoring gauges across the country. The long-term data (annual maxima) from these gauges are used to develop Intensity-Duration-Frequency (IDF) curves for the location, which in turn define maximum average rainfall intensities for different durations of rainfall, for different frequencies (i.e. typically the 2, 5, 10, 25, 50 and 100-year return period values). Civil engineers, and in particular water resources engineers, rely on these IDF values to design SWM infrastructure appropriately.

An inherent assumption in the application of IDF values is that the data is stationary. Stationarity is founded upon the idea that natural systems are variable only within a defined boundary. It implies that any variable, including precipitation, has a probability density function that does not change with time, and whose characteristics can be estimated from a time series of data collected in the field (Milley et al, 2008). With projected changes in climate variability, precipitation included, it is likely that changes will also occur with the characteristics of the associated probability density function. Thus, SWM infrastructure that was designed using existing or historically available IDF data may be impacted by an expected increase in rainfall intensity for a given return period, leading to increases in flooding and adverse impacts to downstream receivers (through reduced quantity control from existing SWM facilities, among other considerations).

In Ontario, municipalities are most commonly tasked with the management of SWM systems, which are required to service both existing and planned development areas. This paper reviews the work that one specific municipality, the City of Welland, has taken to proactively consider and plan for the impacts of climate change. A recent project example is presented, which applied a highly resolute hydrologic/hydraulic model to more specifically assess the implications of a range of climate-change altered rainfall scenarios, both with respect to the change in performance for existing infrastructure, as well as the implications to re-design to better account for these impacts. The results of these analyses are discussed, along with the impact to different stakeholders, including the municipality and designers\practitioners.

# 2 BACKGROUND

## 2.1 Municipal Initiatives

The City of Welland is located within the central portion of the Regional Municipality of Niagara in Southern Ontario, along the Welland River and Welland Canal, which connect Lake Erie and Lake Ontario. It has a population of approximately 50,631 and covers an area of some 81 $km^2$ (City of Welland, 2019).

The City of Welland has been proactively considering and planning for the impacts of climate change through the completion of several vulnerability assessments. A comprehensive climate change risk assessment and adaptation planning study was previously completed for the City of Welland in 2012 (Amec, 2012). The assessment encompassed the City's stormwater and wastewater collection infrastructure including the wastewater treatment plant. The risk assessment followed the climate change vulnerability assessment protocol developed by the Public Infrastructure Engineering Vulnerability Committee (PIEVC) of Engineers Canada.

A component of the risk assessment study included reviewing the City of Welland's approved IDF rainfall data, which is currently based on data from 1963 from Buffalo, New York (City of Welland, 2013). A review of the IDF data actually determined that more current, local IDF data would generate larger rainfall depths and intensities for less frequent, longer duration events, but that the current 1963 data would still generate larger values for more frequent, shorter duration events. As such, the 1963 IDF data remains the approved rainfall data source for the City of Welland.

Subsequent to the completion of the comprehensive study, a cost benefit analysis of an updated storm drainage design standard was also undertaken (Amec, 2014). As part of this assessment, the actual performance of SWM infrastructure was also assessed. The performance of a SWM facility (SWMF) for the Brookhaven Estates subdivision was assessed using the event-based hydrologic model (MIDUSS) created by the developer's engineering consultant (Kerry T. Howe Engineering Limited, 2006). The existing SWMF design was assessed under climate-change altered rainfall data, as well as re-designed using climate change-altered rainfall data. The former analysis determined that although performance of the SWMF would be decreased under climate change-altered rainfall, the SWMF would be able to convey all storm events safely (albeit with reduced freeboard) with the exception of the 100-year storm event for two (2) of the more formative climate-change rainfall scenarios. The latter re-design effort indicated that additional reconstruction costs (including both land and construction costs) would vary between approximately $120,000 and $420,000, depending on the scenario selected.

As part of the preceding study, the potential impacts of climate change-altered rainfall on the storm sewer design of the same subdivision were also assessed using a conventional design sheet approach – Rational Method and Manning's Equation (Amec, 2014). When applying the same design standard (i.e. 1 in 2 year rainfall event for the design of storm sewers), the results indicated that for many of the climate change-altered rainfall scenarios, no changes to the storm sewer design would result. The exception would be some of the more extreme scenarios, which resulted in increased costs of between 11 and 24% above the base design. The preceding results were also presented at the EIC Climate Change Technology Conference (Nimmrichter et al, 2015).

While the preceding analyses are considered informative, they are based on more simplistic methods of analysis. These approaches inherently do not consider the dynamic nature of an integrated SWM system, including factors such as backwater/tailwater, inlet capacity, surface ponding, and others. Further, with potentially increasing rainfall intensities and depths, stormwater runoff events would be expected to use the major conveyance system more frequently in the future, which is typically not assessed in conventional design approaches, or assessed only in simplified terms. The City of Welland has accordingly expressed an interest in undertaking a more resolute hydrologic/hydraulic modelling assessment of a SWM system, in order to better understand what impacts may be expected from climate change-altered rainfall.

### 2.2 South Pelham Subdivision

The South Pelham Subdivision is a 22 ha ± detached residential development located within the City of Welland. The subdivision was developed in phases, with the majority of the development constructed in 2002. The first infill at the north of the subdivision, referred to as the Whispering Pines Development (3.2 ha ±) was constructed over the course of multiple years, generally in the 2004-2014 period. A second infill cul-de-sac (Forest Ridge Court), referred to as the Pine Creek Estates Development (2.4 ha ±) was constructed later, in approximately 2015. A final development, referred to as the Maple Terrace View Development (0.5 ha ±) is currently under construction. The study area is presented in Figure 1.

The subdivision is serviced by roadway storm sewers, which were originally sized for the City's design criteria, namely the 1 in 2-year storm event. There are also a large number of rear-yard catch basins (RYCBs); 37 in total. The storm sewer collection system outlets to a conventional end of pipe wet pond SWMF, with a footprint of approximately 0.5 ha. The SWMF provides quality and quantity control for the contributing drainage, and outlets via a dedicated storm sewer on the adjacent roadway (South Pelham Road) to the receiving watercourse approximately 200 m to the south (Drapers Creek), which drains an upstream area of approximately 379 ha.

The subdivision has previously experienced drainage system issues. A "rain on snow" event in December 2013 resulted in the surcharging of the stormwater collection system. This surcharge resulted in overflow from a rear-yard catchbasin within the Pine Creek Estates Development, which ultimately resulted in surface flooding impacts to an existing residence to the south, external to the subdivision. A number of supplemental assessments were completed by the City, however these investigations were focused on the operation of the SWMF during the flooding event in question. Given the City's overall concerns with respect to climate change impacts to SWM infrastructure, and the known issues with the South Pelham subdivision specifically, Wood Environment & Infrastructure Solutions (Wood) was retained by the City to undertake a more detailed hydrologic/hydraulic modelling assessment of the South Pelham subdivision, with a specific focus on the potential impacts of climate change-altered rainfall (Wood, 2019).

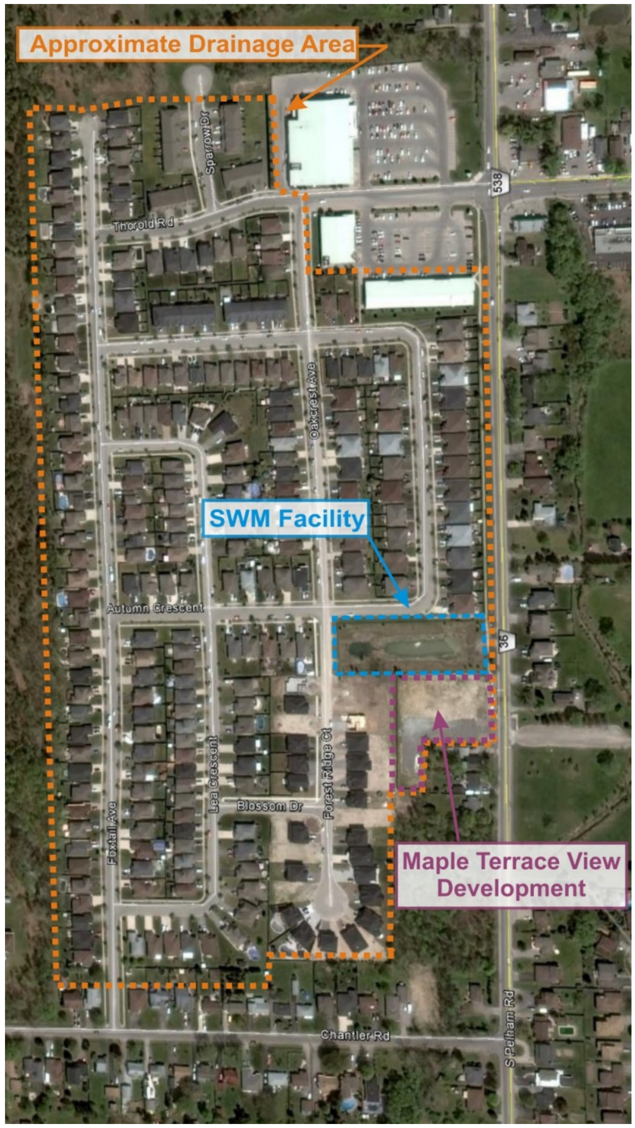


Figure 1: South Pelham Subdivision

# 3 METHODOLOGY

## 3.1 Model Development

In order to undertake the required assessment, a robust modelling platform is required, which is capable of simulating both hydrology (simulated flow responses for different climate change-altered rainfalls) and hydraulics (minor (storm sewer) and major (overland flow) systems as well as storage reservoirs and impacts of tailwater from downstream receivers). Based on the preceding requirements, PCSWMM was selected, which is a graphical user interface (GUI) and decision support system for the US EPA Stormwater Management Model (SWMM).

Available storm drainage and grading plans obtained for the South Pelham subdivision were reviewed and applied to generate subcatchment boundaries for the model area. A total of eighty-nine (89) subcatchments were delineated for areas draining to the SWMF, with an average subcatchment area of 0.24 ha. Imperviousness for the drainage area was estimated based on current (2015) aerial photography. Based on this review, an average imperviousness of 70% was estimated for areas draining towards the roadway right-of-way (roadway, sidewalk, driveways, and a portion of front roof areas), and 45% was estimated for rear-yard drainage (majority of roof area and rear yard area). Based on this approach, a total imperviousness of 56% was estimated for contributing drainage to the SWMF.

In order to account for external flows to Drapers Creek, simulated peak flows from an area watershed study were applied as external inputs to the localized hydraulic modelling of the watercourse (Aquafor Beech, 2012). A total drainage area of 379 ha is estimated upstream of the SWMF outlet. The external area flows are included for a reasonable estimate of tailwater conditions and are not the focus of the climate change assessment, thus the external flows have been applied for the 2 through 100-year storm events as required for rainfall events not influenced by climate change.

An “all pipes” approach was applied, thus all storm sewer links, including rear-yard catchbasin leads have been included in the modelling. The dual drainage creator tool within PCSWMM was applied to generate a parallel major system for roadway drainage, whereby the base of the major system is assumed equal to the rim elevation of the storm sewer maintenance hole. Representative roadway transects are then applied for flow conveyance. The minor and major drainage systems are linked through the use of dual orifices, representing both the catchbasin grate and the catchbasin lead (Senior et al, 2017).

The SWMF is also modelled as a storage reservoir (defined by a stage-surface area function), with the outlet control structure components represented explicitly by pipes and orifices in order to allow for the potential for tailwater conditions. The storm sewer outlet for the SWMF is also explicitly included, to its connection with Drapers Creek. Open channel sections representing Drapers Creek were also included in the modelling, using cross-sections from previous studies (Aquafor Beech, 2012). The hydraulic elements for the modelling are presented in Figure 2. Storm sewer elements are presented in yellow, overland flow conveyance (roadways) in black, and open channel sections in light blue. Pink elements represent orifices.

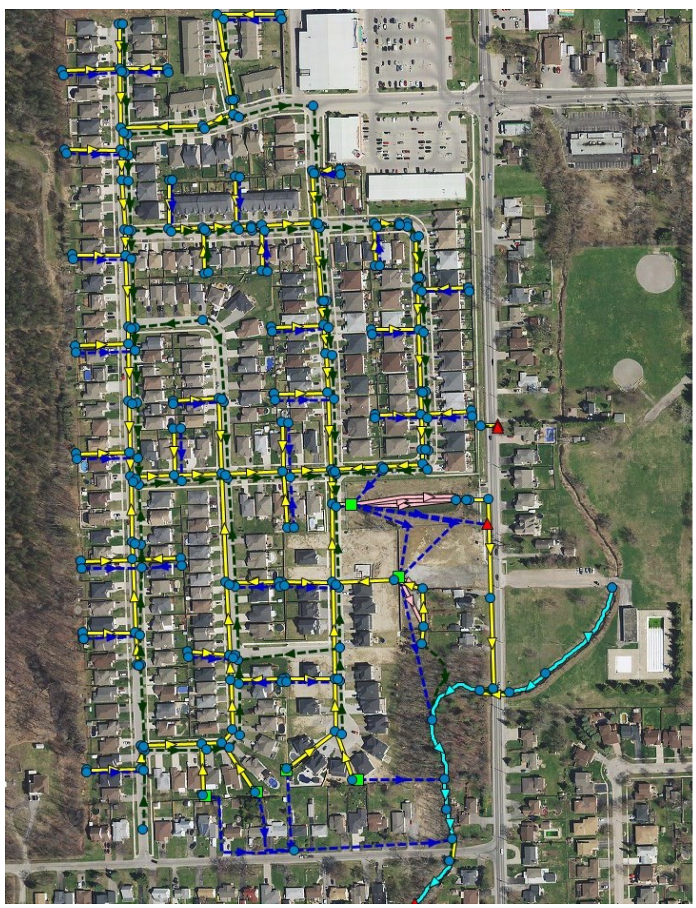

Figure 2: Modelled Hydraulic Elements

### 3.2 Climate Change-Altered Rainfall

Numerous different climate change-altered rainfall scenarios have been previously reviewed and applied for climate change assessments for the City of Welland (Amec, 2012).

The approach selected for this work uses a statistical model that derives the sensitivity of extreme precipitation to climate conditions from the historical climate information for the site. In this case the historical climate was characterized by observations of monthly average temperature and monthly total precipitation at the nearby Port Colborne weather station. The statistical model was fit to the local climate data and the historical monthly precipitation maxima, using a form of regression. Information about future monthly average temperature and monthly total precipitation was obtained from the output of 112 runs of General Circulation Models (GCMs) sourced through the World Climate Research Programme's Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model dataset (WCRP, 2009). The process of how the data was aggregated specifically for the study area is outlined elsewhere (Amec, 2012).

Ultimately, the 112 projections used to characterize future climate conditions produced an equal number of estimates of projected precipitation intensities. For reporting purposes, these results were aggregated into the mean, maximum and 90th percentile non-exceedance value of precipitation intensity for each duration and return interval for both the 2020 and 2050 timeframes.

In addition to the preceding, climate change influenced IDF data is now more readily available through other sources. One example is the University of Western Ontario’s IDFCC Tool, available at http://www.idf-cc-uwo.ca (Simonovic et al, 2016). Climate change-altered rainfall has been extracted from this tool for 2050, using the RCP 4.5 and RCP 8.5 emission forcing scenarios (as per IPCC, 2014). Another example is the Ontario Climate Change Data Portal (OCCDP) IDF rainfall tool, available at http://ontarioccdp.ca/, which is run by the Institute for Energy, Environment and Sustainable Communities (IEESC) at the University of Regina. Data has been extracted from the OCCDP for 2050 for the grid cell (25 km x 25 km) encompassing the City of Welland. Data is also available through the Ontario Ministry of Transportation (MTO) IDF Curve Lookup tool (http://www.mto.gov.on.ca/IDF_Curves), for which data has been extracted for 2050 based on the point location representative of the City of Welland.

The preceding provides a suite of ten (10) different sets of climate change-altered IDF dataset scenarios for the City of Welland, which were used to assess the impacts to the South Pelham Subdivision and its SWM system. The IDF data has been used to generate design storm hyetographs based on a 24-hour duration Chicago Design Storm Distribution (Keifer and Chu, 1957).

## 4 ANALYSIS AND RESULTS

### 4.1 Storm Conveyance System

The performance of the storm conveyance system (including both storm sewers and overland flow conveyance) was assessed using the dual drainage modelling for the range of simulated climate change-altered rainfall inputs. Table 1 presents the simulated change in system performance for both the 2-year return period (for the assessment of the storm sewer system) and the 100-year return period (for the assessment of major overland flow).

For the storm sewer system, the simulated results (2-year design event, consistent with original design criteria) indicate that an average of eight (8) storm sewer segments would be expected to be flooded (hydraulic gradeline above surface) under climate change-altered rainfall conditions. Rear-yard catch basin (RYCB) leads do not indicate any notable increase in reverse flow (backflow) for the 2-year storm event due to climate change impacts.

Table 1: Difference in Simulated Storm Conveyance as compared to Base IDF Data

| | 2-year | | 100-year | |
|---|---|---|---|---|
| | Increase in flooded storm sewers | Increase in RYCB Leads with Reverse Flow | Increase in overland nodes with maximum depth > 0.25 m | Increase in RYCBs with maximum depth > 0.15 m |
| Minimum | 0 | -1 | 2 | 0 |
| Maximum | 23 | 1 | 5 | 1 |
| Average (2020) | 10 | 1 | 3 | 0 |
| Average (2050) | 7 | 0 | 4 | 0 |
| Average (All) | 8 | 0 | 4 | 0 |

For the overland flow system, the simulated results (100-year design event, consistent with design criteria) indicate that an average of four (4) additional major system nodes would have a simulated maximum depth of 0.25 m, which is typically the limit at which depths would be expected to exceed the roadway right-of-way and begin to impact private property. This depth is also typically a threshold for safe passage of vehicles. Similar to the results for the 2-year storm event, RYCBs do not indicate any notable increase in ponding depth on private property due to climate change impacts.

In addition to assessing the performance of the existing stormwater conveyance system under climate change-altered rainfall, the impacts of climate change-altered rainfall on the design of the storm sewer system was also reviewed using the developed dual drainage modelling. The roadway storm sewer system has been re-designed based on the varied 2-year rainfall associated with the ten (10) different sets of climate change-altered rainfall, such that the theoretical full flow capacity of each segment of storm sewer (neglecting tailwater and backwater impacts) is not exceeded. Results are presented in Table 2.

Table 2: Additional Storm Sewer Upgrades (2-year Storm Event) as compared to Base IDF Data

| | Additional Sewers increased by 1 pipe size | Additional Sewers increased by 2 pipe sizes | Additional Sewers increased by 3+ pipe sizes | Additional upgraded storm sewers | Additional Incremental Cost |
|---|---|---|---|---|---|
| Minimum | 3 | -4 | 0 | 3 | $70,000 |
| Maximum | 13 | 4 | 12 | 25 | $990,000 |
| Average (2020) | 8 | 0 | 8 | 16 | $650,000 |
| Average (2050) | 7 | 0 | 8 | 15 | $585,714 |
| Average (All) | 8 | 0 | 8 | 15 | $605,000 |

The results indicate that between 3 and 25 sections of storm sewer (average of 15) would require upgrading to ensure unsurcharged conveyance of climate change-altered rainfall. These simulated required increases in pipe size are generally split evenly between minor upgrades (increase of 1 standard pipe size) and more substantial upgrades (increase of 3 or more standard pipe sizes). Approximate costs have been estimated in Table 2 based on 3x the available supply cost for concrete storm sewer pipe of the required diameter (class 65-D – 2016 pricing) in order to account for installation costs and appurtenances. Based on this analysis, additional construction costs would vary between $70,000 to $990,000, with an average of $605,000. This represents a notable additional construction cost.

### 4.2 Stormwater Management Facility

The performance of the end of pipe SWMF was also assessed using the developed hydrologic/hydraulic modelling for the range of simulated climate change-altered rainfall inputs. Table 3 presents a summary of differences in the simulated performance of the SWM facility as compared to the base IDF condition for the 2-year and 100-year storm events, in order to present the range in results.

Table 3: Difference in Simulated SWMF Performance as compared to Base IDF Data

| | 2-year Return Period | | | 100-year Return Period | | |
|---|---|---|---|---|---|---|
| | Discharge ($m^3/s$) | Operating Level (m) | Volume ($m^3$) | Discharge ($m^3/s$) | Operating Level (m) | Volume ($m^3$) |
| Minimum | 0.02 | 0.10 | 298 | 0.017 | -0.01 | -21 |
| Maximum | 0.13 | 0.46 | 1,493 | 0.453 | 0.03 | 167 |
| Average (2020) | 0.07 | 0.25 | 784 | 0.158 | 0.01 | 61 |
| Average (2050) | 0.07 | 0.24 | 763 | 0.259 | 0.02 | 97 |
| Average (All) | 0.07 | 0.24 | 770 | 0.228 | 0.01 | 86 |

For the 2-year storm event, the simulated results indicate a notable variability in the increase in SWMF discharge, operating level and volume between minimum and maximum results. Average results are generally consistent for 2020 and 2050 results; results for 2050 are in fact somewhat less, which is considered attributable to the greater number of datasets in this case (7 for 2050 as compared to 3 for 2020) and in particular the generally lower predicted values for the IDFCC, OCCDP, and MTO datasets. Operating levels for the 2-year storm event would be on average 0.24 m greater than the base IDF case, which is notable given that the originally designed active operating range (i.e. quantity control range above the permanent pool for the 2 through 100-year storm events) is some 1.74 m (Wood, 2019).

The results for the 100-year storm event indicate only minor changes in operating level and volume, but more notable increases in the outflow discharge. This is due to the fact that at the levels simulated, the SWMF would be spilling uncontrolled to the south, thus flows increase notably for only minor increases in operating level. These additional uncontrolled spills have the potential to impact downstream properties, particularly given that a defined overflow spillway was not included in the originally approved design.

In addition to the analysis of the performance of the SWMF, the difference in the potential design of the SWMF (if based on climate change-altered rainfall) has also been undertaken. This assessment has assumed that the SWMF would be required to maintain the same pre-development peak flow targets for the 2 through 100-year storm events as applied in the originally approved design (which did not use climate change-adjusted rainfall). Table 4 presents the results of this assessment and the associated additional required storage volume. In addition, the associated additional land requirements have been calculated, based on a theoretical enlargement to the south and accounting for typical SWMF side slopes. Land costs have also been calculated, based on $150/$m^2$ (typical for the City of Welland, as per Amec, 2014). Construction costs have been estimated at $65/$m^3$, in order to account for excavation and off-site disposal, as well as fine grading and landscaping.

The results indicate that for one (1) of the climate change-altered rainfall scenarios, no increase in storage would actually be required (the MTO IDF Tool). All of the other nine (9) scenarios however indicate that an increase in sizing of the SWMF would be required, with volume increases ranging from 760 m3 (6%) to 4,083 m3 (32%), and an average increase of 18%. These increased storage volumes translate to a corresponding increase in land requirements (17% on average). Total additional costs (beyond the base cost of the SWMF) average approximately $375,000, which would be a significant additional expense for developers. In the case of the South Pelham Subdivision, this increase is hypothetical, as the SWMF is land locked, with no available undeveloped land available for expansion. This would also be expected to be the case for many other existing SWMFs, given the typical high value of land and the need to optimize SWMF extents and the associated development. Where land is available, the relative cost may in fact be higher, due to private ownership and the development value of the land.

Table 4: Additional Requirements for Re-Designed SWMF as compared to Base IDF Data

| | Additional Volume ($m^3$) | Additional Volume (%) | Additional Land ($m^2$) | Additional Land (%) | Estimated Additional Land Costs | Estimated Additional Construction Costs | Estimated Total Additional Costs |
|---|---|---|---|---|---|---|---|
| Minimum | 0 | 0% | 0 | 0% | $0 | $0 | $0 |
| Maximum | 4,083 | 32% | 2,453 | 29% | $370,000 | $270,000 | $640,000 |
| Average (2020) | 1,933 | 15% | 1,166 | 14% | $183,333 | $130,000 | $313,333 |
| Average (2050) | 2,515 | 20% | 1,514 | 18% | $231,429 | $170,000 | $401,429 |
| Average (All) | 2,340 | 18% | 1,409 | 17% | $217,000 | $158,000 | $375,000 |

## 5 SUMMARY AND FUTURE CONSIDERATIONS

The results presented in this paper provide an overview of the potential range of impacts more intense rainfalls associated with climate change may have upon both the performance and design of SWM related infrastructure.

With respect to the storm conveyance system, the simulated results indicate that a greater number of storm sewer segments would be expected to be flooded for the 2-year design event, which could impact upon connected drainage systems. For the 100-year design event, a larger number of overland locations are indicated as having depths greater than 0.25 m, which would could impact adjacent private properties (flooding beyond the public right-of-way) and also render vehicle passage more difficult, including emergency vehicles. Re-designing the storm sewer system after the fact to provide additional capacity (as per the costs presented in Table 2) is a costly endeavor. Given the economies of scale, incorporating additional capacity or buffer into the storm sewer system at the initial design stage would be a more efficient and effective solution than addressing requirements retroactively. The City of Welland is currently considering a revised design standard for storm sewers which would potentially address this requirement.

With respect to the simulated performance of the end of pipe SWMF, the results indicate that a large amount of the available storage volume would be consumed for the 2-year storm event. For the 100-year storm event, a notable increase in spill/overflow would be expected. In the specific case of the South Pelham Subdivision SWMF, this would result in spill to the south, towards private property, which could result in potential impacts to both lives and property. The assessment of the potential re-design of the SWMF indicates an average additional volume and land requirement (beyond base IDF) of approximately 18%, with an associated average additional cost (land plus construction) of $375,000. In the case of the South Pelham Subdivision SWMF, this potential expansion is theoretical only, as the SWMF is land locked by existing and ongoing development. Similarly to the consideration of storm sewers, incorporating additional volume or land buffer during the design stage would have provided a greater opportunity to adapt to the potential impacts of increased rainfall from climate change. Notwithstanding, it is acknowledged that given the high value of land in development areas this may not always be practical, unless explicitly mandated in the relevant design criteria.

## ACKNOWLEDGEMENTS

The authors of this paper gratefully acknowledge the participation and co-operation of the Corporation of the City of Welland for its contributions to this paper and the project as a whole.

## REFERENCES


Amec Environment & Infrastructure. 2012. *Stormwater and Wastewater Infrastructure Assessment. National Engineering Vulnerability Assessment of Public Infrastructure to Climate Change – City of Welland*. Amec Environment & Infrastructure, Burlington, Ontario, Canada.

Amec Environment & Infrastructure. 2014. *Cost:Benefit Assessment of an Updated Storm Drainage Design Standard – City of Welland*. Amec Environment & Infrastructure, Burlington, Ontario, Canada

Aquafor Beech. 2012. *Central Welland River Floodplain Mapping Update Study. Niagara Peninsula Conservation Authority*. Aquafor Beech, Mississauga, Ontario, Canada.

City of Welland. 2013. *Municipal Standards*. City of Welland, Ontario, Canada.

City of Welland. 2019. *City of Welland*. Available at: http://www.welland.ca.

Interovernmental Panel on Climate Change. 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland.

Kerry T. Howe Engineering Limited. 2006*. Rainbow Country Estates (Brookhaven Estates) Stormwater Management Report*, *City of Welland*. Kerry T. Howe Engineering Limited, St. Catharines, Ontario, Canada.

Keifer, C. J. and Chu J.H. 1957. Synthetic Storm Patten for Drainage Design. *Journal of the Hydraulics Division*, ASCE, HY 4, **1332**, 1-25.

Milley, P.C.D, Betancourt, J, Falkenmark, M., Hirsch, R.M., Kindzewicz, Z.W., Lettenmaier, D.P., Stouffer, R.J. 2008. Stationarity Is Dead: Whither Water Management? *Science*, **319**(1).

Nimmrichter, P., Scheckenberger, R, and Ingebrigsten, M. 2015. Assessing Climate Change Risk to Stormwater & Wastewater Infrastructure. *EIC Climate Change Technology Conference*. Paper Number 1570085317.

Senior, M, Scheckenberger, R, and Bishop, B. 2017. Modelling Catchbasins and Inlets in SWMM. *Journal of Water Management Modelling*, **26**:C435.

Simonovic, S.P., Schardong, A, Sandink, D, and Srivastav, R. 2016. A Web-based Tool for the Development of Intensity Duration Frequency Curves under Changing Climate. *Environmental Modelling & Software Journal*, **81**:136-153

Wood Environment & Infrastructure Solutions. 2019. *Cost:Benefit Assessment of an Updated Storm Drainage Design Standard – Review of Stormwater Management Issues for the South Pelham Subdivision - City of Welland*. Wood Environment & Infrastructure Solutions, Burlington, Ontario, Canada.

World Climate Research Programme (WCRP). 2009. *Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model dataset. Archive of downscaled climate projections*. Available at: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/