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RISK-BASED PERFORMANCE ASSESSMENT OF STORMWATER DRAINAGE NETWORKS UNDER CLIMATE CHANGE: A CASE STUDY IN THE CITY OF KINGSTON, ON

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ABSTRACT

The ability of urban drainage systems to operate satisfactorily under a wide range of possible future hydrologic conditions is an important system characteristic. As weather patterns shift, it is important to understand how local infrastructure may be affected as extreme rainfall events have the potential to cause direct and indirect damages to communities. Continuous simulation in SWMM 5.1 coupled with synthetic precipitation files generated using GCM outputs were used to assess the risk-based performance in terms of reliability, resiliency and vulnerability of an urban drainage system in the City of Kingston, Ontario, Canada. The study drainage network investigated in this paper never experienced a flooding or surcharging event (i.e. 100% system reliability), however, an observed positive trend in the ratio of conduit depth to full depth over time indicates the potential for unsatisfactory system performance in the future as a result of changing hydrologic conditions due to climate change.

Keywords: hydrologic impact assessment; climate change; flood risk; stormwater management

1. INTRODUCTION

Climate change impacts in Ontario include higher temperatures and increases in magnitude and frequency of extreme weather events (IPCC 2013). These changes in climate variability may increase stormwater runoff and consequently, the potential for localised flooding in urban areas. While the need for Canadian municipalities to adapt to changing climatic conditions is pertinent there is a lack of necessary expertise within municipalities for implementing current research related to the impact of climate change on design methods (Srivastav et al. 2014). The primary objective of the research is to contribute to the advancement of decision making capabilities of municipalities and watershed management authorities in addition to providing a better understanding of the existing and future operation and performance of stormwater infrastructure under future climate scenarios.

Urban stormwater management systems are typically designed to meet performance standards based on historical climate events which are assumed to be stationary (Peck et al. 2012). Based on the evidence from climate change impact studies, this assumption is unsound and stormwater management systems within the built environment will need to meet performance expectations under climatic conditions that are different from historical climate.

Research incorporating non-stationarity into climate projections in order to revise and update the design storm concept is abundant. Mailhot and Duchesne (2010) introduced a procedure for revising the design criteria of urban drainage infrastructure by integrating information about climate projections for extreme rainfall, expected level of system performance and expected lifetime of the infrastructure system through a concept of a critical reference year T years into the future. This methodology recognizes the addition of the climate change dimension could negatively impact system performance over time. Therefore, some evaluation of the performance level should be conducted in order to develop an adaptation strategy that will maintain the desired performance (and corresponding risk) to an acceptable level over time (Mailhot and Duchesne, 2010). The concept of designing for the future provides the context and impetus for this paper. The research aims to establish methods for evaluating existing and future stormwater drainage systems using a continuous simulation approach in order to assess and quantify system performance in terms of risk over time.

Several studies have implemented the risk-based performance criteria presented by (Hashimoto 1982). However, most apply the concepts presented to evaluate water resource system capacities for case studies focusing on reservoir systems (peak demand and periods of drought) (e.g., Labadie 2004) or studies establishing sustainability criteria for water resource systems (e.g., Sahely et al. 2005, Loucks and Gladwell 1999). To date, no studies have applied the risk-related performance criteria in a Canadian drainage system assessment context. The research presented adapts and applies the performance criteria of Hashimoto (1982) to evaluate the reliability, resiliency and vulnerability of an urban drainage network in the City of Kingston. These performance measures are of particular importance during periods of extreme weather and will be useful in evaluating how an existing or proposed storm system will perform in an uncertain future.

1.1 Study Site

The methodology presented in the research is applied to a study site in the City of Kingston. Kingston is an eastern-Ontario municipality located on Lake Ontario, at the mouth of the St. Lawrence Cataraqui Rivers (Figure 1).

Figure 1: Kingston, Ontario, Canada

Kingston has a humid continental climate with warm summers and no dry season. The annual precipitation averages 952 mm, of which approximately 17% falls as snow. Kingston is projected to experience an increase in average annual precipitation of 3% and 8% by 2020 and 2050 (MacIver and Auld 2013). Meteorological data utilized in this paper was obtained from the *Kingston Pumping Station* (Meteorological Services of Canada (MSC) ID: 6104175) in Kingston, Ontario, Canada. Examined in this paper is a 6.4 ha subarea (Figure 2) within the LO-09 catchment. The study area features residential land use and is serviced by approximately 0.75 km of separated storm sewers.

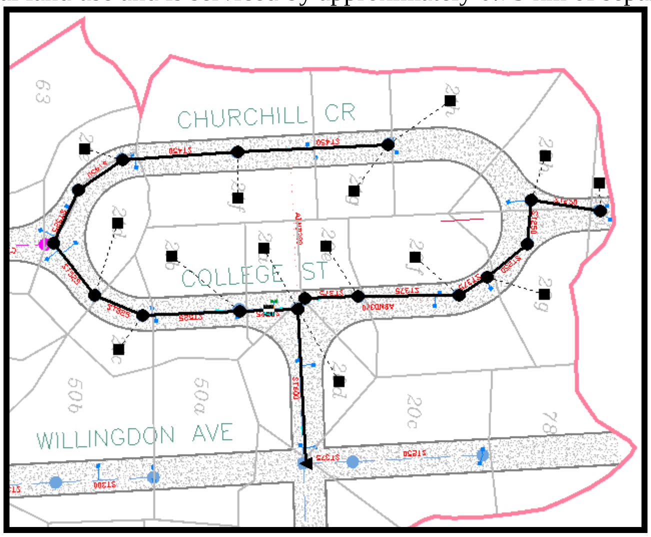


Figure 2: LO-09 catchment and 6.4 ha study area

2. METHODOLOGY

2.1 Model development in SWMM 5.1

The drainage network presented in Figure 2 was modeled using EPA SWMM 5.1. SWMM 5.1 is a dynamic rainfall-runoff model used for single-event to long-term simulation of the surface/subsurface hydrology quantity and quality from primarily urban areas. SWMM 5.1 is used worldwide for planning, analysis, and design related to drainage system components, floodplain mapping of natural channel systems, generating nonpoint source pollutant loadings, evaluating LIDs for sustainability goals, etc. More details on SWMM 5.1 features and characteristics are provided in Rossman (2007). The time-series outputs generated from continuous simulation will facilitate the risk-based performance assessment

2.2 Generation of precipitation time-series

The mathematical models and procedures used in this research integrated precipitation data from existing Environment Canada hydro-meteorological station with outputs obtained from Global circulation models (GCMs) provided by the Canadian Centre for Climate Modelling and Analysis (CCCma).

GCMs are numerical models representing the physical processes in the atmosphere, ocean, cryosphere and land surface, they are the most advanced tools in climate science currently available for simulating the response of the global climate system to increasing greenhouse gas emissions (IPCC 2013). GCMs provide an understanding of climate change under different future emission scenarios and provide a way to incorporate climate change into stormwater management and planning (Srivastav et al. 2014). The main drawback to GCMs are the temporal and spatial scale (typically 100 km by 100 km) of outputs which are incompatible with smaller study sites like those of a city. In order to accommodate the application of assessing the impacts of climate change at the local level, downscaling techniques of GCM outputs were be utilized to provide suitable temporal and spatial scales.

A change factor approach (CFA) was used to downscale GCM outputs as the method has been widely used in hydrological impact studies (e.g., Prudhomme et al. 2010, Anandhi and Frei 2011, Darch and Jones 2012, Kay and Jones, 2012, Karamouz et al. 2013, Zahmatkesh et al. 2014). The approach consists of first establishing a baseline precipitation time-series for the area of interest, then changes in the equivalent precipitation variable for the GCM or Regional Climate Model (RCM) grid box closest to the target site were be determined. For example, a difference of 10.5 mm might occur by subtracting the mean GCM precipitation values for 1971–2010 from the mean of the 2050s. Next, the temperature change suggested by the GCM (in this case, +10.5 mm) is simply added to each day in the baseline time series (Diaz-Nieto and Wilby 2005).

The future emission scenarios used in this paper is based on RCP 2.6. The results using RCP 2.6 will represent the range of uncertainty or possible range of performance under changing climatic conditions. The intent of RCP scenarios is to provide a framework by which the process of building simulation experiments can be streamlined. By utilizing the above mentioned RCPs in the proposed research, it would be applicable to compare the results obtained in this study to others in the field.

Two precipitation files were developed in order to drive the SWMM 5.1 rainfall runoff model, a baseline (historical) and a climate change (CC) record. The baseline file was generated using the observed precipitation record (no RCP). The CC scenario was created by modifying the observed record using the results of selected GCMs (change fields).

2.3 Description of risk-based performance criteria

Using concepts presented in (Hashimoto 1982), the time-series outputs produced from continuous simulation modeling in SWMM 5.1 were used to evaluate the performance of the study area within the LO-09 urban drainage system in terms of the criteria of reliability, resiliency and vulnerability.

The operational status of a drainage network can be described as either satisfactory or unsatisfactory. The occurrence of unsatisfactory performance is described in this research as a failure, where a failure corresponds to a flood event. The analysis on system performance focuses on system failure, defined as any output value in violation of a performance threshold and can be described from three different viewpoints; (1) Reliability – how often the system fails (α or C_R); (2) Resiliency – how quickly the system returns to a satisfactory state once a failure has occurred (γ or C_{RS}); and, (3) Vulnerability – how significant the likely consequences of failure may be (v or C_V) (Hashimoto, 1982). A brief description of the criteria is as follows.

A criterion, *C*, is defined for each drainage network conveyance element, where an unsatisfactory value is one where a conveyance element (i.e. conduit) is unable to provide a pre-determined level of service. The time series of simulated values of water depth, X_t, will then be evaluated to some future time, *T*. Each storm system element will have its own range of satisfactory, *S* and unsatisfactory, *F*, values defined by the criterion, *C* (Hashimoto 1982):

$$\begin{aligned} &If\ \ X_t \geq C\ \ then\ \ X_t \in S\ \ and\ \ Z_t = 1 \\ &\qquad\qquad else\ \ X_t \in F\ \ and\ \ Z_t = 0 \end{aligned}$$

Another indicator is defined, W_t, which indicates a transition from a satisfactory to and unsatisfactory state (Hashimoto 1982):

$$W_t = \begin{cases} 1, & X_t \in F\ \ and\ \ X_{t+1} \in S \\ 0, & otherwise \end{cases}$$

If the periods of unsatisfactory X_t are then defined as $J_1, J_2, \ldots, J_N$, then reliability (1), resilience (2) and vulnerability (3) indices can be defined (Hashimoto 1982):

[1] $$C_R = \frac{\sum_{t=1}^{T} Z_t}{T}$$

[2] $$C_{RS} = \frac{\sum_{t=1}^{T} W_t}{T - \sum_{t=1}^{T} Z_t}$$

[3] $$C_V = max\left\{ \sum_{t \in J_i}^{T} C - X_t,\ \ i = 1, \ldots, N \right\}$$

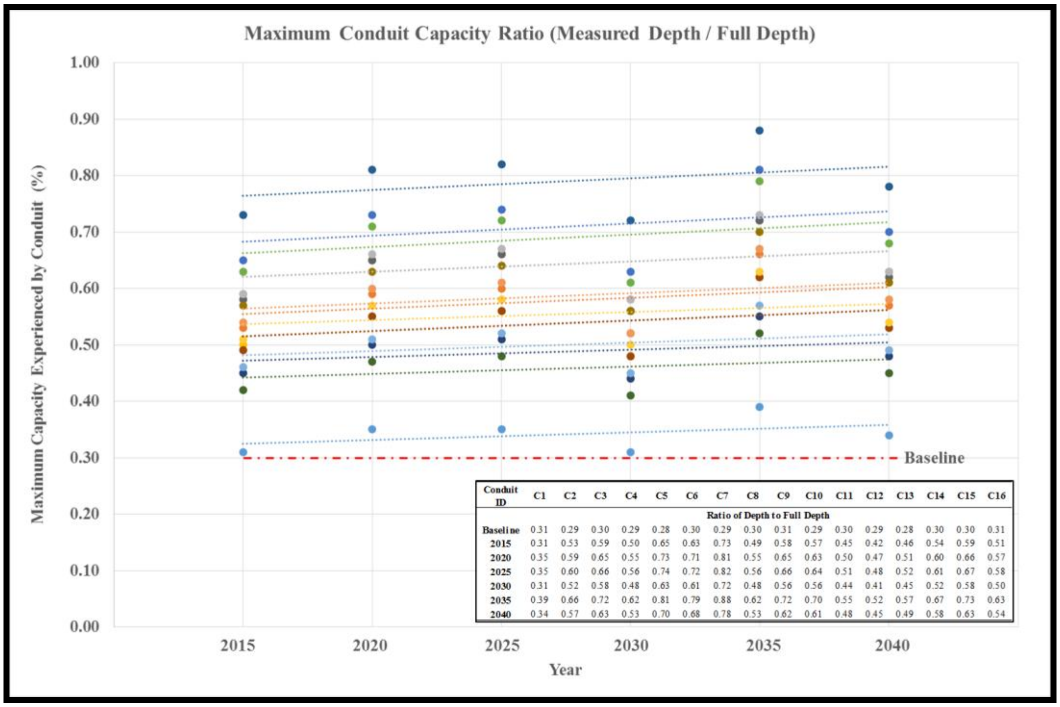
Calculations are performed for each conveyance element, or sewer segment in the drainage network. The time series outputs from SWMM 5.1 were analyzed in order to measure and quantify the performance of the drainage network. Performance calculations were performed at 5-year time intervals. The main purpose of the intervals is to provide a reference point in monitoring how the performance of the drainage system progresses over time, a very important system characteristic under the non-stationary climate hypothesis.

3. PRELIMINARY RESULTS FOR STUDY SITE

Two simulations were conducted in SWMM 5.1, one with the baseline record and another with the modified record that incorporated climate change projections until the year 2040. The outputs produced from continuous simulation modeling in SWMM 5.1 were used to evaluate risk-related aspects of system performance, more specifically the criteria of reliability, resiliency and vulnerability.

The case study drainage system was observed to never operate in an unsatisfactory state for both the baseline and CC experiments, where and unsatisfactory period is defined as an occurrence of the conduit capacity exceeding 100%, as shown in Figure 3. Therefore, equation (1) yields a completely reliable system (C_R = 1.0) for both scenarios and consequently system resilience (C_{RS}) and vulnerability (C_V) were determined to be zero using equations (2) and (3).

Although the system operated in a satisfactory state throughout the duration of the simulation, it was observed that the maximum volume experienced by the system increased over time. This supports the non-stationarity hypothesis indicating that system performance will decline over time. Figure 3 illustrates the maximum capacity experienced by each conduit during the 70-year (1971-2040) continuous simulation.



Conduit ID	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16
	Ratio of Depth to Full Depth															
Baseline	0.31	0.29	0.30	0.29	0.28	0.30	0.29	0.30	0.31	0.29	0.30	0.29	0.28	0.30	0.30	0.31
2015	0.31	0.53	0.59	0.50	0.65	0.63	0.73	0.49	0.58	0.57	0.45	0.42	0.46	0.54	0.59	0.51
2020	0.35	0.59	0.65	0.55	0.73	0.71	0.81	0.55	0.65	0.63	0.50	0.47	0.51	0.60	0.66	0.57
2025	0.35	0.60	0.66	0.56	0.74	0.72	0.82	0.56	0.66	0.64	0.51	0.48	0.52	0.61	0.67	0.58
2030	0.31	0.52	0.58	0.48	0.63	0.61	0.72	0.48	0.56	0.56	0.44	0.41	0.45	0.52	0.58	0.50
2035	0.39	0.66	0.72	0.62	0.81	0.79	0.88	0.62	0.72	0.70	0.55	0.52	0.57	0.67	0.73	0.63
2040	0.34	0.57	0.63	0.53	0.70	0.68	0.78	0.53	0.62	0.61	0.48	0.45	0.49	0.58	0.63	0.54

Figure 3: Ratio of conduit depth to full depth during baseline and projected time-slices.

4. SUMMARY

The methodology and results of the research will provide new tools and methods for engineers, planners and decision makers to assist them in the development and assessment of stormwater drainage infrastructure under climate change. Although this paper only presents brief comparison of baseline conditions to a single climate change scenario (CC), additional climate scenarios can be considered in order to form a range of potential future climates as indicated in Figure 4. This will address the limitations and magnitude of uncertainty associated with the selection of a single climate scenario (Srivastav et al. 2014).

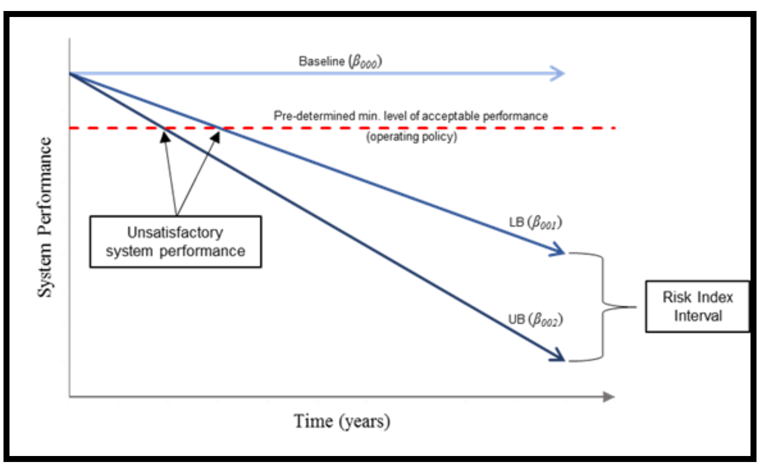


Figure 4: Time-series plot of existing drainage system performance for multiple climate scenarios.

With the inclusion of additional climate scenarios, the decision maker is provided with two essential pieces of information; (1) how the current drainage system is operating and how they can expect it to operate in the future under a range of climate scenarios; and, (2) provide the decision maker with a planning horizon or a target year for adaptation and development of implementation strategies by identifying the time period where the system will perform unsatisfactorily. This unsatisfactory period can be determined by interpolating down from the intersection of the lower-bound and upper-bound values at the pre-determined acceptable performance level. The results presented are specific to the case study drainage system, however, the procedures presented in this paper are transferable to any region or municipality. Applying the methods can improve the decision support framework for the assessment of municipal urban stormwater infrastructure in light of a changing climate.

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