THESIS

ASSESSING OF PERFORMANCE OF STORMWATER CONTROL MEASURES UNDER VARYING MAINTENANCE REGIMES

Submitted by

Alfy Joseph George

Department of Civil and Environmental Engineering

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Fall 2020

Master's Committee:

Advisor: Mazdak Arabi

Sybil Sharvelle
Michael Ronayne

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ABSTRACT

ASSESSING OF PERFORMANCE OF STORMWATER CONTROL MEASURES UNDER VARYING MAINTENANCE REGIMES

Stormwater control measures (SCMs) are being installed worldwide to curb urbanization impacts such as flooding, stream degradation, nutrient pollution, and contaminant loading in receiving water bodies. Regular inspection and maintenance are important to ensure long term effective performance of SCMs over their design life. This study investigates the performance, reliability, and time to failure of permeable pavement, a filtration based SCM, as a function of the design life and different maintenance strategies. The Stormwater Management Model (SWMM) is used to simulate performance of infiltration based SCMs under different climate and operational conditions including different maintenance regimes. A probabilistic approach is developed to characterize the risk, reliability and vulnerability of the system. Performance data including the effects of clogging and maintenance was obtained from comprehensive literature review of numerous international studies on performance of SCMs under different maintenance activities and strategies. The method of Sobol' global sensitivity analysis is used to evaluate the predictive uncertainty in the estimated surface overflow/bypass flow, runoff, and infiltration to characterize uncertainty in the input parameters of SWMM. Risk-based evaluation metrics are defined and characterized to assess the performance and probability of failure of the systems. A hazard function approach is used to characterize the time to failure of the systems under full, partial, and no maintenance regimes. Results indicate that maintenance plays a significant role in the simulated flow budgets and the performance of infiltration based SCMs. The time to failure of the systems is substantially increased by partial maintenance, while full maintenance marginally increases the time to failure compared to the partial maintenance regime. The analysis can be used to develop effective maintenance strategies for SCMs to ensure longevity and reliability of SCMs over their design life.

ACKNOWLEDGEMENTS

I would like to first thank my thesis advisor, Dr. Mazdak Arabi for his continuous support and guidance throughout this entire project and for his excellent mentorship that has immensely benefited both my academic and professional career. Thank you, Mazdak, for being a wonderful leader and a great friend throughout my master's program. I would like to also thank my committee members Dr. Sybil Sharvelle and Dr. Michael Ronayne for their valuable inputs and guidance in this project. Thank you, Sybil, for your guidance for the past three years and thank you Mike, for your enthusiastic support and feedback.

I would also like to thank Tyler Dell and Mahshid Ghanbari for their participation and input in this project. I would also like to thank my colleagues and friends from Glover 119 and civil engineering for their moral support and advice throughout the years.

Finally, I cannot express how grateful I am for my wonderful family and friends that have supported and encouraged me to pursue my dreams and have constantly pushed me to be better person in life. Pappa, Mummy, Jimmy, and Jincy, thank you for believing in me. Mary Ann, thank you so much for pouring into my life all these years. Rick and Clare, thank you for your love and friendship and thank you for believing in me and investing in my academic dream. Tom and Vickie, thank you for making me feel at home in Fort Collins. To my fiancé, Stacy, thank you for standing by me and being my biggest stronghold and support right from the beginning of my dream to move to the US for graduate school. I will be forever grateful to you. This accomplishment has only been possible with the support of all the people mentioned above. Thank you.

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Chapter 1. Introduction

Rapid development of urban areas leads to an increase in impervious surface cover, which causes significant changes to the volume and quality of stormwater runoff produced in these areas. This results in higher peak runoff, increased runoff volumes, larger runoff velocities, shorter lag times, increased water contamination and more frequent downstream flooding (Blecken et al., 2017; Burszta-adamiak & Mrowiec, 2013; Dreelin et al., 2006; Emerson et al., 2010; North Carolina Department of Transportation, 2010; Sadeghi et al., 2018; N. Siriwardene et al., 2007; Wang et al., 2018; Xiao & McPherson, 2011). These changes affect the downstream receiving bodies in terms of physical, chemical, and biological conditions (Wang et al., 2018; Xiao & McPherson, 2011). In the past few decades, filtration-based stormwater treatment technologies have been installed across the globe and are commonly used in areas without conventional urban drainage systems as useful techniques to reduce the impact of urbanization on receiving waters (Dreelin et al., 2006; Kandra et al., 2015). Various nomenclature has been attributed to these systems (Blecken et al., 2017) including stormwater best management practices (BMPs), stormwater control measures (SCMs), sustainable urban drainage systems (SUDS) and implementation strategies such as water sensitive urban design (WSUD), low impact development (LID) and green infrastructure (GI). The term stormwater control measure (SCM) is used hereafter in this article.

Like any infrastructure, the assumption is that these SCMs are constructed, operated, and maintained properly. However, implemented practices and past studies have shown that improper design or lack of periodic maintenance quickly tends to cause these systems to fail resulting in poor performance of capturing and treating the urban stormwater runoff. While these systems are very effective in managing and treating urban stormwater, over time they tend to lose their permeability and drainage capacity, reducing their performance due to the clogging of contaminants of stormwater containing suspended solid matter such as dirt, sand, and debris (Deo et al., 2010; Winston, Al-Rubaei, Blecken, & Hunt, 2016). Stormwater infiltration systems have a history of failures due to clogging of the system within a short period of performance (Siriwardene et al., 2007). The importance of periodic and well-informed inspection and maintenance has been raised more frequently in recent studies involving the performance of SCMs across the world in the past couple of decades (Blecken et al., 2017; Erickson et al., 2018).

A number of studies that have been carried out involving the clogging of SCMs, have all reported the existence and importance of clogging and maintenance in these filtration-based SCMs. (Brown & Borst, 2013; Deo et al., 2010; Emerson et al., 2010; Kandra et al., 2015; Lee et al., 2015; Razzaghmanesh, 2018). Dirt and debris can clog underlying layers of an SCM and over time can result in complete failure of functionality of the system, stopping the capture, treatment, and infiltration of stormwater into the soil. This causes the stormwater coming into the system to leave the system as surface overflow or bypass flow. Some of the most common filtration-based SCM technologies in these studies include bio-retention/rain gardens, grass swales, infiltration trenches, ponds, and permeable pavement systems.

In this study, permeable pavement is modelled in SWMM to represent infiltration based SCMs to understand effects of clogging and maintenance on performance and reliability of these SCM technologies. Permeable pavement systems are very popular structures for management of both urban runoff quality and quantity, designed to infiltrate rainfall and stormwater runoff through the pavement surface. These are either monolithic or modular systems that can be constructed with pervious concrete, porous asphalt, permeable paver blocks, or other manufacturing materials (Lee et al., 2015; UDFCD, 2019; Yong et al., 2013). Permeable pavement systems are widely used in urban environments as they can be used to potentially reduce additional expenditures and land consumption for conventional stormwater drainage system providing storage and treatment onsite. The effective life of a pavement is defined as the number of years it is in service, until which the hydraulic performance of the system drops to a level where the drainage 'design storm event' is unmanageable and maintenance is required. This process is known as "pavement clogging" (Yong et al., 2013). It is evident from literature, that clogging of a stormwater infiltration system determines the design lifespan of infiltration systems, but a quantitative understanding of the clogging process is currently very limited (Siriwardene et al., 2007).

Clogging can be defined as the processes of reducing porosity and permeability and hence decreasing the infiltration rate and hydraulic performance of the system due to physical, biological, and chemical processes (N. R. Siriwardene et al., 2007). The time taken for a SCM to clog depends on the impervious areas contributing to stormwater runoff and the capture ratio of the SCM itself (N. R. Siriwardene et al., 2007). Clogging of the underlying layers has been identified to be the main limiting factor of a SCM and studies have shown rapid exponential decline in the performance of these systems (Kandra et al., 2015; Razzaghmanesh, 2018).

With wide implementation of SCMs in urban and suburban stormwater management plans, it is very necessary to understand the process of clogging as impacted by maintenance of these systems. Enhanced understanding of clogging enables prediction of performance efficacy over design life. As the need arises to enhance longevity of SCMs, the role of maintenance has become imperative as it notably influences the performance of these SCMs. EPA's Stormwater Management Model (SWMM; Rossman, 2015) is used in the study to model the SCM. SWMM is an open source, dynamic hydrologic-hydraulic water quality model that can model both urban and suburban hydrological processes as well as track the quantity and quality of runoff through an

SCM (Wang et al., 2018). With the concerning growth for how climate change is affecting the urban water infrastructure and the increased interest in adoption of alternative green infrastructure strategies as a potentially cost-effective stormwater management option, SWMM is the preferred simulation tool for addressing such needs (Niazi et al., 2017) and is arguably the most widely utilized stormwater model in the world (Burszta-adamiak & Mrowiec, 2013).

The objectives of this study are to (1) characterize clogging in infiltration based SCMs (2) examine the role of maintenance on the performance of these systems in accordance with design life using a probabilistic approach and (3) develop an analytical hazard function for the characterization of reliability and mean time to failure of these SCMs.

This study conducts a global sensitivity analysis to characterize the predictive uncertainty of parameters influencing the model outputs such as total runoff and bypass flow that show the performance of the SCM. The data showing the performance of SCMs under different regimes of maintenance is also included in the sensitivity analysis to understand the clogging phenomenon and the effect of maintenance on the performance of the SCMs. Extreme value analysis is used to calculate return period and return levels for bypass flow intensity of SCMs and a hazard function is developed to characterize reliability of SCMs under different maintenance regimes. This study will help community and city planners to better design SCMs and have a better understanding of the functionality of these systems. It can also provide further recommendations and techniques to maintain these systems for improved performance over a longer period of time.

Chapter 2. Methods

2.1 General Methodology

Comprehensive literature review shows that the understanding of clogging and maintenance is significant to improve the performance of SCMs over their design life. Assumptions were made using clogging data (years taken for SCM to clog) and maintenance activities from 55 studies to categorize the clogging data into full, partial, and no maintenance regimes. A rigorous method of Sobol' global sensitivity analysis was conducted to propagate parametric uncertainty of SCM outputs in the SWMM model and characterize the role of maintenance in the performance of these SCMs over their design life. We developed a hazard function to characterize the reliability and determine the failure density of SCMs and calculate the time to failure under full, partial, and no maintenance regimes.

2.2 Characterization of Clogging in Infiltration SCMs

A detailed literature review of over 55 studies involving clogging and maintenance of permeable pavements over the past two decades was carried out. The locations of these systems were across the world, predominantly North America and Europe. All these studies included the different types of permeable pavement tested for clogging and permeability and had detailed observations on the age of the systems during the monitoring period, the maintenance activities conducted, and the effect of these maintenance activities on the performance of the permeable pavement systems. In these studies, the performance efficiency was reported based on the ability of maintenance activity to restore the permeability and infiltration of the permeable pavement. Literature showed that over the past decades different maintenance practices were carried among these SCMs to help restore their efficiency in performance by increasing their infiltration capacity

(Blecken et al., 2017; Drake et al., 2013; Erickson et al., 2018; Razzaghmanesh, 2018). These different maintenance activities have shown varying success to restore permeability and infiltration capacity of SCMs.

Some of the maintenance activities conducted on the permeable pavements were vacuum sweeping, regenerative air sweeping, pressure washing, and even sometimes replacement of underlying layers. It was found that certain maintenance activities were more effective in restoring the infiltration capacity of the system for most of the studies. From this observation, assumptions were made to group these maintenance activities to categorize the years taken for the system to clog and have a significant reduction in functional performance under different levels of maintenance. These maintenance activities were categorized into three regimes as no maintenance, partial maintenance, and full maintenance.

No maintenance was where there was no maintenance activity conducted for the permeable pavement during the entire monitoring period. Partial maintenance was where periodic maintenance activities were conducted either semi-annually or annually and full maintenance was where maintenance activities were conducted either monthly or in a more periodic routine even including complete replacement of layers of the SCM.

The assumptions made to categorize the years to clog into different regimes of maintenance were: (1) time interval between maintenance activities conducted during the monitoring period. (2) the type of maintenance activity and their effectiveness in restoring the permeability of the underlying layers of the SCM. (3) Capture ratio of the system and the land use density of the treated area.

Table 1. Clogging Data of Permeable Pavement Systems including the Age and Maintenance Activities

Region	Pavement Type	Age (years)	Land Use	Captur e Ratio	Maintenance Regime	Maintenance Activities	Reference
UK	PICP	15	HD	1	Full Maintenance	No Maintenance up to 15 years; after which complete replacement of soil and storage layer	(Pratt et al., 1995)
FRA	PICP	10	HD	1	Partial Maintenance	Moistening followed by sweeping and sweeping followed by suction did not help restore performance but suction alone and high-pressure water jetting with suction provided restoration of infiltration as preventive maintenance and rehabilitation maintenance.	(Baladés et al., 1995)
CAN	PICP	2	MD	0.5	No Maintenance	No Maintenance	(Kresin et al., 1997)
CAN	PICP	8	HD	1	Partial Maintenance	Periodic sweeping and vacuuming can help regenerate to full infiltration capacity	(James & Gerrits, 2003)
USA	PICP	6	MD	1	No Maintenance	No Maintenance during monitoring period	(Brattebo & Booth, 2003)
UK	PICP	2	HD	0.5	No Maintenance	No maintenance during period of study	(Abbot & Comino, 2003)

CHN	PP	4	MD	0.25	No Maintenance	No maintenance during the entire period after installation. Estimated to completely restore the infiltration, replacement of layers after 15 years	(Hou et al., 2008)
CAN	PICP	17	HD		Partial Maintenance	Vacuuming and sweeping once every three to four years help to restore partial or full infiltration. Higher maintenance frequencies may be required in areas with greater traffic volumes.	(Toronto Regional and Conservation Authority, 2008)
CAN	PICP	4	HD	1	Partial Maintenance		
CAN	PICP	12	MD	1	Partial Maintenance		
CAN	PICP	10	MD	1	Partial Maintenance		
AUS	PICP	20	MD	0.5	Full Maintenance	Recommended maintenance including sweeping and washing and full replacement after 20 years.	(Pezzaniti et al., 2009)
CAN	PC	1	HD	1	Partial Maintenance	Power washing can push debris deeper into the voids of the underlying layers. Sweeping may remove the debris on the surface but does not improve permeability or infiltration of the	(Henderson & Tighe, 2011)
CAN	PC	2	HD	1	Partial Maintenance		
CAN	PC	2	HD	0.5	Partial Maintenance		
CAN	PC	2	HD	1	Partial Maintenance		

CAN	PC	1	HD	1	Partial Maintenance	system. Washing the surface with large diameter hose can dislodge debris deep in voids and renew permeability. Pressure vacuuming and sweeping can also help restore permeability significantly.	
USA	PA	3	HD	0.25	No Maintenance	No maintenance done throughout the period of study.	(Roseen et al., 2012)
CAN	PICP	7	HD	0.25	Full Maintenance	Regenerative air and vacuum sweeping trucks help restore 50% of permeability. Performing periodic sweeping and vacuuming annually can help improve performance of the system. Mechanical sweeping annually did not help in surface permeability performance.	(J. Drake et al., 2012)
CAN	PC	4	HD	1	Partial Maintenance		
CAN	PC	18	Unspecified	1	Partial Maintenance	Pressure washing, Vacuum sweeping and combination of pressure washing, and vacuum sweeping was introduced to improve	(Chopra et al., 2010)
CAN	PC	18	Unspecified	1	Partial Maintenance		
CAN	PC	16	Unspecified	1	Partial Maintenance		

CAN	PC	14	Unspecified	1	Partial Maintenance	the infiltration performance of the system. Vacuum sweeping did not produce significant improvement in infiltration. Pressure washing helped in partial improvement of performance and combination of pressure washing and vacuum sweeping helped restore complete permeability of pervious concrete.	
CAN	PC	14	Unspecified	1	Partial Maintenance		
CAN	PC	13	Unspecified	1	Partial Maintenance		
CAN	PC	10	Unspecified	1	Partial Maintenance		
CAN	PC	9	Unspecified	1	Partial Maintenance		
CAN	PC	6	Unspecified	1	Partial Maintenance		
CAN	PC	6	Unspecified	1	Partial Maintenance		
CAN	PA	1	MD	0.5	Partial Maintenance	Vacuum sweeping maintenance on the PA did not significantly improve the permeability of the system. Repeated wetting and vacuum sweeping can help restore the permeability of the system	(Duin et al., 2008)
CAN	PICP	2	LD	1	Partial Maintenance	Hand sweeping regenerative air sweeping did not help restore infiltration and is not a recommended maintenance practice to improve the long-term performance of the	(J. A. P. Drake et al., 2013)
CAN	PICP	4	MD	0.5	Partial Maintenance		
CAN	PICP	8	MD	1	Partial Maintenance		
CAN	PICP	13	MD	0.5	Partial Maintenance		

CAN	PICP	2	MD	0.25	Partial Maintenance	system. Low suction or high suction vacuuming and pressure washing can be an effective maintenance treatment to rejuvenate permeability of the system.	
CAN	PC	2	LD	1	Partial Maintenance		
USA	PICP	2	HD	1	No Maintenance	No maintenance during period of study	(Brown & Borst, 2014)
USA	PC	4	HD	0.25	No Maintenance		
USA	PICP	1	MD	0.25	Partial Maintenance	Regenerative air sweeper truck including a combination of vacuuming and mechanical sweeping helps to restore only partial infiltration of the system. Compressed air treatment only provides short term infiltration restoration and not long term. Vacuum head with hydro pressure washing and vacuuming improved long-term effective performance of the system.	(Kazemi et al., 2017)
USA	PICP	1	MD	0.25	Partial Maintenance		
NZ	PICP	2	HD	0.5	No Maintenance	No maintenance done throughout the period of	(Fassman & Blackbourn, 2010)

NZ	PICP	2	HD	1	No Maintenance	study. Pressure washing is not recommended for maintenance but can help recover permeability of the system.	
NZ	PICP	1	MD	0.25	No Maintenance		
NZ	PICP	1	HD	1	No Maintenance		
ND	PICP	4	LD	1	No Maintenance		(Boogaard et al., 2014)
AUS	PICP	12	HD	1	No Maintenance		
AUS	PICP	8	LD	1	No Maintenance		
USA	PICP	2	HD	0.5	Full Maintenance	Mechanical street sweeper or regenerative air sweeper did not help restore permeability except a little for PICP but either vacuuming or pressure washing, or a combination of vacuuming and pressure washing can help restore permeability. Pressure washing is not recommended for a continuous period of time as it can cause the debris particles to go into the underlying layers and can restrict infiltration.	(Winston, Al-Rubaei, Blecken, Viklander, et al., 2016)
USA	PICP	1	HD	0.5	Full Maintenance		
USA	PICP	1	HD	0.25	Full Maintenance		
SWE	PA	21	HD	1	Full Maintenance		
SWE	PA	28	HD	1	Full Maintenance		
SWE	PICP	4	HD	0.25	Full Maintenance		
SWE	PICP	9	HD	0.25	Full Maintenance		

2.3 Model Development in SWMM

Infiltration-based SCMs can be modeled in SWMM as low impact development (LID) controls (UDFCD, 2019; Wang et al., 2018) such as rain gardens/bio-retention, permeable pavement, grass swale, infiltration trench, and sand filter. SWMM is an open source, dynamic hydrologic-hydraulic water quality model that can model both urban and suburban hydrological processes as well as track the quantity and quality of runoff through an SCM (Wang et al., 2018).

A 1-acre, single-unit sub-catchment was delineated in SWMM as the drainage area. Urban Drainage Flood Control District (UDFCD, 2019) describes that modeling a LID practice in SWMM is based on the four-component land use model that is used by the Colorado urban hydrograph procedure (CUHP) and SWMM. This conceptual model typically represents a drainage area by four components as follows: (1) Directly Connected Impervious Area (DCIA), (2) Unconnected Impervious Area (UIA), (3) Receiving Pervious Area (RPA) and (4) Separate Pervious Area (SPA) (Figure 1). DCIA is the impervious area that drains to the storm drain system or stream without flowing over surfaces that would allow for infiltration. UIA is the impervious area that drains to a receiving area, where there is an opportunity for infiltration. RPA is the pervious that receives runoff from UIA and allows for infiltration and SPA is the pervious area that does not receive any runoff from impervious surfaces.

Typically, an SCM is designed to capture and infiltrate the water quality capture volume (WQCV), which is a design parameter for sizing these systems (Park et al., 2013). WQCV corresponds to the runoff volume produced from storm events such as the 80th percentile of runoff producing storms and this volume varies depending on local rainfall data (UDFCD, 2019).

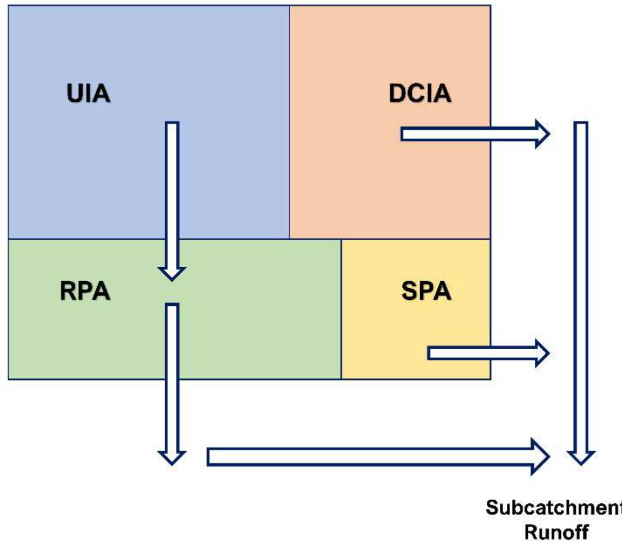

Figure 1. Four component land use model used to represent the functioning of a LID Unit in SWMM

The purpose of designing SCMs based on the WQCV is to both improve the water quality and reduce hydro-modification and the associated impacts on receiving waters. According to the UDFCD design criteria manual, the WQCV disregards storm events with no anticipated runoff, which are precipitation events with the depth of 0.1 inches and smaller. The depth of 0.6 inches is the optimal target for the WQCV which corresponds to the 80th percentile of runoff-producing storms. Hence, we are interested in the storm events greater than 0.1 inches to assess the performance of the SCM in capturing and treating the WQCV.

In this study, according to the runoff reduction method (Piza & Rapp, 2018; UDFCD, 2019) to capture and treat the WQCV, the sub-catchment was modeled to function as an UIA:RPA pair that includes both the impervious drainage area that contributes stormwater runoff and the receiving SCM. This simple model was developed to conduct a multi-parametric, Monte Carlo simulation that mimics the hydrology of any typical watershed to characterize the critical input factors that control or influence the output and performance of SCMs. LID is a distributed method of runoff source control, that uses surface and landscape modifications located on or adjacent to impervious areas that generate most of the runoff in urbanized areas. For this reason, SWMM considers LID controls to be part of its subcatchment object, where each control is assigned a fraction of the subcatchment's impervious area whose runoff it captures (Rossman & Huber, 2016).

The model was developed to run a continuous simulation for a period of 30 years from 1989 to 2018. The daily rainfall and evapotranspiration data for this period were obtained from the (NOAA) national center for environmental information for the Fort Collins Area. The Horton infiltration method was used in SWMM to obtain the soil characteristics of the drainage area. A graphical user interface of SWMM was developed to conduct the Monte Carlo analysis by selecting randomly generated input parameters sets, running the model, and recording the output variables for each of the parameter sets.

2.4 Representation of SCMs in SWMM

SCMs can be represented as LID control units in SWMM (Wang et al., 2018). In this study, permeable pavement is modeled as a low impact development (LID) control unit to represent an infiltration-based SCM. A typical permeable pavement consists of either pervious concrete, asphalt, or permeable interlocking pavers as the surface layer, a subsurface layer consisting of an optional non-native soil or sand layer and a gravel storage layer in the bottom which contains an underdrain system (UDFCD, 2019). A cross-sectional representation of the permeable pavement LID unit in SWMM is shown in Figure 2. The surface layer receives both the direct rainfall and runoff captured from the drainage area. It loses water through the infiltration into the soil layer below it, evapotranspiration of ponded surface water, and the remaining water goes off as surface runoff or bypass flow. The infiltrated water percolates into the storage layer which loses the water either by exfiltration into the underlying natural soil or is collected through an underdrain system.

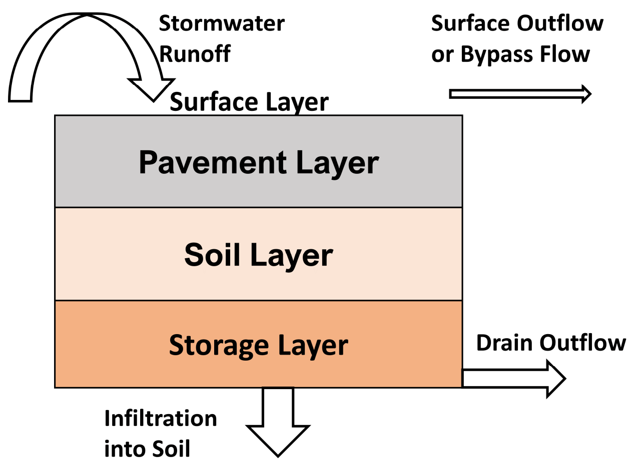

Figure 2. Cross-sectional representational model of a permeable pavement LID unit in SWMM

The various layers of a permeable pavement are represented as:

Surface Layer;

$$\frac{\partial d_1}{\partial t} = i + q_0 - e_1 - f_1 - q_1 \quad \textit{Equation (1)}$$

Pavement Layer;

$$D_4(1 - F_4)\frac{\partial \theta_4}{\partial t} = f_1 - e_4 - f_4 \quad \textit{Equation (2)}$$

Sand Layer;

$$D_2\frac{\partial \theta_2}{\partial t} = f_4 - e_2 - f_2 \quad \textit{Equation (3)}$$

Storage Layer;

$$\phi_3\frac{\partial d_3}{\partial t} = f_2 - e_3 - f_3 - q_3 \quad \textit{Equation (4)}$$

Where, d_1 = depth of water stored on the surface [ft]; θ_2 = Soil layer moisture content [volume of water / total volume of soil]; d_3 = depth of water in the storage layer [ft]; θ_4 = Moisture content of the permeable pavement layer; i = Precipitation rate falling directly on the surface layer [ft/sec]; q_0 = inflow to the surface layer from runoff captured from other areas [ft/sec]; q_1 = surface layer runoff or overflow rate [ft/sec]; q_3 = storage layer underdrain outflow rate [ft/sec]; e_1 = Surface ET rate [ft/sec]; e_2 = soil layer ET rate [ft/sec]; e_3 = storage layer ET rate [ft/sec]; f_1 = infiltration rate of surface water into the soil [ft/sec]; f_2 = percolation rate of water through the soil layer into the storage layer [ft/sec]; f_3 = exfiltration rate of water from the storage layer into the native soil [ft/sec]; f_4 – exfiltration rate of water from the pavement layer into the sand layer [ft/sec]; ϕ_1 = Void fraction of any surface volume [fraction of freeboard above surface without vegetation]; ϕ_2 = Porosity of the soil layer; ϕ_3 = Void fraction of the storage layer; D_1 = freeboard height for surface ponding [ft]; D_2 = thickness of soil layer [ft]; D_3 = thickness of storage layer [ft]

Stormwater-runoff surface inflow is the inflow to the surface layer of the SCM, that comes from both direct rainfall and runoff from impervious drainage area captured by the SCM unit. Exfiltration would normally depend on the depth of the stored water and the moisture profile of the soil beneath the SCM unit or can be assumed as the user-supplied saturated hydraulic conductivity of the native soil beneath the SCM. Due to clogging, over time, the SCM is susceptible to ponding on the surface as the infiltration into the ground decreases and any ponded surface water in excess of maximum freeboard or depression storage height becomes immediate overflow. This immediate overflow also known as surface outflow or overflow runoff is the bypass flow that leaves the system. This bypass flow represents the output from the system that is produced due to clogging in the SCM. This output is evaluated to characterize the performance of SCMs under the application of different maintenance regimes and to develop an analytical procedure for characterization of reliability and time to failure to be able to make predictions on the design life of these systems.

2.5 Representation of Clogging and Maintenance in SWMM

The hydraulic conductivity of the underlying layers of SCM decreases over time as a continuous function of the cumulative sediment mass load passing through it. Cumulative sediment mass can be replaced by cumulative inflow volume by assuming a long-term average sediment inflow concentration. This inflow volume can be adjusted for void space in the relevant LID layer so that hydraulic conductivity reduction becomes a function of the number of the layer's void volumes processed by the LID unit. If clogging factor is defined as the number of layer void volumes treated to completely clog the layer and assumes a linear loss of conductivity with number of void volumes treated, then the conductivity *K* at some time t can be estimated as:

$$K(t) = K(0)\left[1 - \frac{Q(t)V_{void}}{CF}\right] \quad \textit{Equation (5)}$$

where, *K(0)* = initial conductivity of media; V_{void}= volume of void space per unit area in the LID layer; *Q(t)* = cumulative inflow volume per unit area to the LID unit through time *t*; *CF* = clogging factor of pavement.

Because clogging is a long-term process, it would only apply to continuous time series simulations of several months or more duration. The clogging rate constant or clogging factor (CF) can be computed from the number of years T_{clog} it takes to fractionally reduce an infiltration rate to a degree F_{clog}. Clogging factor for a permeable pavement is estimated in SWMM using:

$$CF = \frac{I_a(1+R_{LID})T_{clog}}{\varphi D(1-F)F_{clog}} \quad \textit{Equation (6)}$$

where T_{clog} = number of years to reduce the infiltration rate to a degree of F_{clog}; I_a= annual rainfall over the site [in]; R_{LID} = pavement capture ratio; *φ* = porosity of pavement layer; *D* = thickness of pavement layer [in]; f = fraction of surface area covered by permeable pavement; F_{clog}= degree of clogging [fraction].

In this study, the data observed are under the assumption that the system is completely clogged and therefore the degree of clogging F_{clog} is 1. The data collected from literature includes the number of years taken to completely clog an infiltration SCM, T_{clog} for each level of maintenance. This T_{clog} is a key parameter in characterizing the role of maintenance in the performance of infiltration based SCMs.

2.6 Identifying Uncertain Input Parameters

Initially, a total of 26 input parameters of SWMM were considered for the sensitivity analysis. Based on literature, these 26 parameters contribute to the outputs of the SCMs in SWMM. SCMs in SWMM are complicated models that contain a large number of random inputs whose uncertainties have a significant influence on the model outputs, however, only a few inputs play a critical role in the model (Feng et al., 2019). From these 26 input parameters, the insensitive parameters can be removed to reduce the computation expense (Wang et al., 2018) and provide relevant space to look at the significant and most sensitive parameters influencing the model and their interaction with other parameters. Since it was a hypothetical model not representing any specific location, recommended ranges for each parameter were obtained from various literature, studies and design manuals. Table 2 shows the 26 different parameters that were taken into consideration for the initial sensitivity analysis. All the parameters were assumed to be of uniform distribution for random sampling in generating input parameter sets. From the clogging data of permeable pavements, the number of years to clog for the three regimes of maintenance were found to best fit a gamma distribution.

Table 2. Uncertain input parameters included in SWMM model, the ranges for the parameters and the assumed distribution of parameters.

System Component	Parameter	Range of Values	Unit	Distribution
Subcatchment	Surface Width	100-600	feet	Uniform
	Surface Slope	2-10	%	Uniform
	Impervious	0-100	%	Uniform
	Impervious Manning's n	0.005-0.05		Uniform
	Pervious Manning's n	0.01-0.5		Uniform
	Impervious Depression Storage	0.1-0.3	inches	Uniform
	Pervious Depression Storage	0.2-0.3	inches	Uniform
	Impervious area with Zero Depression Storage	50-80	%	Uniform
Infiltration	Maximum Infiltration Rate	1.96-8.5	inches/hour	Uniform
	Minimum Infiltration Rate	0-1.2	inches/hour	Uniform
	Decay Constant	2-7		Uniform
	Drying Time	2-14	Days	Uniform
LID Component	**Parameter**	**Range of Values**	**Unit**	**Distribution**
Surface Layer	Ponding Depth	6-12	ft	Uniform
Soil Layer	Thickness	8-12	ft	Uniform
	Field Capacity	0.15-0.25	volume fraction	Uniform
	Wilting Point	0.05-0.1	volume fraction	Uniform
	Saturated Conductivity	5-30	inches/hour	Uniform
	Suction Head	2-4	inches	Uniform
	Porosity	0.25-0.35	volume fraction	Uniform
Storage Layer	Thickness	6-36	ft	Uniform
	Porosity	0.2-0.4	volume fraction	Uniform
Pavement Layer	Thickness	3-8	inches	Uniform
	Porosity	0.15-0.25	volume fraction	Uniform
	Permeability	28-1750	In/hr	Uniform
	Capture Ratio	0-5		Uniform
Maintenance Regime	**Parameter**	**No Maintenance**	**Partial Maintenance**	**Full Maintenance**
Gamma Distribution	Shape	2.119	1.3518	1.0455
	Scale	1.7865	5.5125	10.33

2.7 Global Sensitivity Analysis – Method of Sobol

A multi-parametric sensitivity analysis (MSPA) was conducted to characterize the uncertainty and sensitivity of uncertain parameters influencing the outputs of the model. Global sensitivity analysis (GSA) is one of the methods in MSPA that is developed to identify the contributions of uncertainties present in the inputs to the outputs and can identify important inputs and quantify their significance (Chan et al., 1997; Feng et al., 2019; Read & Vogel, 2016; Rosolem et al., 2012). The variance-based method also called the method of Sobol' is a versatile and effective method among a vast variety of available techniques in GSA (Feng et al., 2019; Lamboni et al., 2013). This method has high dimensional model representation (HDMR) and analysis of variance (ANOVA) decomposition which can decompose the variance of a model output depending on each input and their interactions (Feng et al., 2019; Saltelli et al., 2004, 2008). It considers the Sobol indices to express the decomposed variance as being due to variations in a single model input in isolation such as first order index and up to variations due to all possible interactions called the total order index (Link et al., 2018).

Significant features such as model independence, capacity to capture the entire variation range of each input parameter, and the ability to determine the interaction effects among input factors makes the method of Sobol one of the most versatile, effective and robust methods among other available techniques in global sensitivity analysis (Feng et al., 2019; Saltelli et al., 2008) and has been preferred across different applications including hydrological and land surface modelling (Ganji et al., 2016; Rosolem et al., 2012; Wan et al., 2015).

The method of Sobol assumes that input factors are orthogonal, where the conditional variances can be seen as a general variance decomposition scheme proposed by (Sobol, 1990). The total output variance V(Y) for a model with k input factors can be decomposed as

$$V(Y) = \sum_i V_i + \sum_i \sum_{j>i} V_{ij} + \cdots + V_{12\ldots k} \quad \textit{Equation (7)}$$

Where the conditional variance $V_i = V(E(Y|X_i))$ is the first order effect of input X_i on V(Y), $V_{ij} = V\left(E\left(Y\middle|X_i, X_j\right)\right) - V_i - V_j$ represents the second order interaction effects of inputs X_i and X_j on V(Y), and so on and k represents the number of input factors (Saltelli et al., 2004).

The first order (main effects) sensitivity index represents the main effect contribution of each input to the output variance and is represented by (Saltelli et al., 2004, 2008).

$$S_i = \frac{V(E(Y|X_i))}{V(Y)} \quad \textit{Equation (8)}$$

The total effects indices determine the interaction effects that are not captured by the main effects indices and is represented by:

$$S_{T_i} = \frac{V(Y) - V(E(Y|X_{-i})}{V(Y)} = \frac{E(V(Y|X_{-i}))}{V(Y)} \quad \textit{Equation (9)}$$

The total order sensitivity index represents the total contribution of V_i to the total variance V(Y) by including both direct and indirect effects also known as main and interaction effects.

SimLab 2.2 (Saltelli et al., 2004) is a didactical software designed for global uncertainty and sensitivity analysis. These analyses are based on performing multiple model evaluations with probabilistically selected input factors and then use the results of these evaluations to determine the uncertainty in model predictions and the input factors that gave rise to this uncertainty. Initially, about 14000 random sample sets of input parameters were generated for each of these three maintenance regimes and the model was simulated using the Monte Carlo method to record and evaluate the outputs of the model such as total runoff and bypass flow for their parametric uncertainties. In general, a Monte Carlo analysis involves five steps: (1) select a range and distribution for each input variable or input factor which will be used in generation on samples. (2) Generate a sample of elements from the distribution of the inputs previous specified. (3) Feed the model with the sample elements and produce a set of model outputs where these evaluations create a mapping from the space of the inputs to the space of the results which is the basis for subsequent uncertainty and sensitivity analysis. (4) The results of the model evaluations are used as the basis for uncertainty analysis. (5) The results of model evaluations are used as the basis for sensitivity analysis. The framework of SimLab involved three frames: (1) The Statistical Pre-Processor module which generates a sample in the space of the input factors. (2) The Model Execution module which executes the model for each point in the sample of input factors and (3) The Statistical Post Processor module which performs the uncertainty and sensitivity analysis. Once the significant parameters were identified, the analysis was conducted again by only varying the significant parameters and keeping the remaining parameters constant to evaluate the bypass flow characteristics to understand the role of maintenance in the performance of SCMs.

2.8 Bypass Ratio and Design Life Level

As mentioned earlier, SCMs are designed to capture and treat the water quality capture volume (WQCV) which corresponds to the runoff produced by storm events that have a precipitation depth greater than 0.1 inches also known as runoff-producing events. The total number of runoff-producing storm events for each year were identified and only the corresponding bypass flow events were also recorded. This was recorded to characterize the bypass ratio of SCMs over time. Bypass ratio is defined as the ratio of the number of bypass flow events to the number of runoff-producing events in any given year. This helps to understand the frequency response of bypass occurrences under different maintenance regimes.

As the frequency and intensity of bypass flow will change from year to year based on several factors including climate, maintenance, and design, return level plots were developed to understand the performance of the SCM under different maintenance regimes. Design Life Level proposed by (Rootzén & Katz, 2013) was adopted which is used to predict the output response of a design value corresponding to given reliability during a design life period (Yan et al., 2017). In the 30-year simulation period, daily averages of bypass flow intensity (inches/hour) were recorded for the days that had runoff-producing storm events. To determine the DLL, the expected value of bypass intensity produced by the runoff-producing storms under different maintenance regimes were calculated.

The expected value of bypass was obtained from a normal distribution with a mean, μ_x and a standard deviation of $\frac{\sigma_x}{\sqrt{n}}$ of the daily averages of bypass intensity. This is given as:

$$Y \sim N\left(\mu_x, \frac{\sigma_x}{\sqrt{n}}\right) \quad \textit{Equation (10)}$$

where *Y* is the expected value of bypass, μ_x is the mean of daily average bypass intensity, σ_x is the standard deviation and n is the number of sample element sets.

Extreme Value analysis (EVA) was adopted to characterize the expected value of bypass to determine return periods and return levels. EVA is commonly used to characterize extreme events with two primary methods for selecting extremes: Peak over threshold (POT) and block maxima method (e.g. annual maxima). The block maxima method only considers one event per block (e.g., a year) (Coles, 2001) but since bypass can occur multiple times in a year, we used the peak over threshold method to consider all the bypass events occurring in the period of analysis. POT approach is applied in several studies involving flood frequency analysis, which consider minor flooding events with multiple occurrences per year (Sweet et al., 2014; Saeed Far & Abd. Wahab, 2016; Yan et al., 2017; Ghanbari et al., 2019, 2020).

In the operation of SCMs, the extreme event of failure is the bypass flow or surface overflow. A bypass flow event occurs when the SCM cannot capture the corresponding runoff volume according to the WQCV and is lost from the system as surface outflow. These events can occur multiple times in a year depending on the cumulative inflow of runoff depending on the contributing impervious runoff areas (Lee et al., 2015; Siriwardene et al., 2007; Yong et al., 2013). Thus, 0 in/hr. of surface outflow for runoff-producing events was taken to be the threshold and anything above 0 in/hr. was considered as bypass flow exceedance.

Generalized Pareto distribution (GPD) was identified to provide the best fit for intensity of bypasses and the p-values of the Kolmogorov-Simonov Goodness-of-Fit test was larger than 0.05 which supports the validity of the assumed distribution (Gharib et al., 2017). The cumulative distribution frequency for the GPD is given by (Coles, 2001):

$$F_u(x) = Pr(X - u < x | X > u) = \begin{cases} 1 - \left(1 + \frac{\xi(x-u)}{\sigma}\right)^{\frac{-1}{\xi}} \; if \; \xi \neq 0 \\ 1 - exp\left(-\frac{(x-u)}{\sigma}\right) \; if \; \xi = 0 \end{cases} \quad \text{Equation (11)}$$

where x is the daily average bypass intensity in inches/hour, u is the location parameter also knows as the threshold, which here is 0, ξ is the shape parameter and σ is the scale parameter. The maximum likelihood estimation (MLE) was used in MATLAB (MathWorks®) was used to estimate parameters of the GPD model for the bypass response for the different maintenance regimes and their corresponding confidence intervals were also obtained to characterize uncertainty.

2.9 Hazard Function Analysis

In the final step, we propose an analytical hazard function to characterize the reliability of SCMs and calculate the mean time to failure of SCMs under different maintenance regimes. Time to arrival of a certain magnitude or time to failure of systems in excess of a design threshold has become a matter of significant concern among many disciplines (Read & Vogel, 2015, 2016). Hazard function analysis (HFA) also known as survival analysis is primarily to describe the functionality and changes in exceedance probability of an event over time (Read & Vogel, 2016). Time to failure or failure density analysis is a part of HFA that deals with the time that a system is functional until it experiences a failure (Read & Vogel, 2015), in this case, a bypass overflow event due to clogging in an SCM.

The failure rate for many systems generally takes a bathtub shape also known as the bathtub curve in which three distinct life periods can be identified described by (Kapur & Pecht, 2014). They are the early-life period, useful-life period, and wear-out-life period. In the early-life period, the failure rate tends to be high and is caused primarily due to design or construction failures. Useful-life period has a constant failure rate determined by overall functional failure and in the wear-out-life period, after a specific time period, the failure rate increases rapidly caused by aging and degradation which can be due to normal wear of the system or due to poor operation and maintenance (Tung et al., 2006).

The hazard function or failure rate function h(t) is defined as the conditional probability that a bypass flow event occurs in a given time interval and is derived as,

$$h(t) = \begin{cases} a\ (ln(bt) & if\ t > t_0 \\ 0 & if\ t \leq t_0 \end{cases} \quad \textit{Equation (12)}$$

where a and b are the model coefficient estimates of the hazard function,

where $b = \frac{1}{t_0}$ and $h(t_0) = 0$.

The reliability of the system, $p_s(t)$ is defined as the probability that no bypass event occurs in the given time interval and can directly be computed from the failure rate function as:

$$p_s(t) = exp\left[-\int_{t_0}^{t} h(t)\, dt\right] \quad \textit{Equation (13)}$$

and the failure density function $f_T(t)$ can be expressed in terms of the failure rate as:

$$f_T(t) = h(t)\, exp\left[-\int_{t_0}^{t} h(t)\, dt\right] \quad \textit{Equation (14)}$$

Therefore, the reliability of the SCM from equation 8 can be derived as:

$$p_s(t) = \begin{cases} exp[-at\ \ ln(bt)]\ exp[a(t - t_0)] & for\ t > t_0 \\ 1 & for\ t \leq t_0 \end{cases} \quad \textit{Equation (15)}$$

Similarly, from equation 9, the failure density function for the SCM can be derived as:

$$f_T(t) = \begin{cases} a\, ln(bt)\, exp[-at\ \ ln(bt)]\ exp[a(t - t_0)] & for\ t > t_0 \\ 0 & for\ t \leq t_0 \end{cases} \quad \textit{Equation (16)}$$

The hazard function was developed and was used to determine the reliability and time to failure of SCMs under different maintenance regimes.

The time to failure is an important parameter in reliability analysis as it represents the length of time during which a system remains operational (Tung et al., 2006), in this case an SCM. The mean time to failure is the random variable to measured reliability of the system. The mean time to failure is the expected time to failure of a system under a given condition. The mean time to failure is denoted as MTTF and can be derived from the failure density function by:

$$MTTF = \int_{t_0}^{t} t f_T(t)\, dt \quad \textit{Equation (17)}$$

And can be expressed in terms of reliability as,

$$MTTF = \int_{t_0}^{t} p_s(t)\, dt \quad \textit{Equation (18)}$$

Chapter 3. Results

3.1 Clogging and Maintenance

Boxplots were created to visualize the clogging data which shows the age of permeable pavements categorized under no, partial, and full maintenance (Figure 3). Under no maintenance, SCMs tend to clog in less than 5 years whereas as maintenance is introduced, it is quite evident that the performance of SCMs improves, and the tendency to fail due to clogging decreases. Under partial and full maintenance, it can take up to 13 and 20 years respectively for the SCMs to completely clog. This clearly implies the necessity to understand the nature of clogging and shows the importance of appropriate inspection and maintenance to enhance the performance of SCMs.

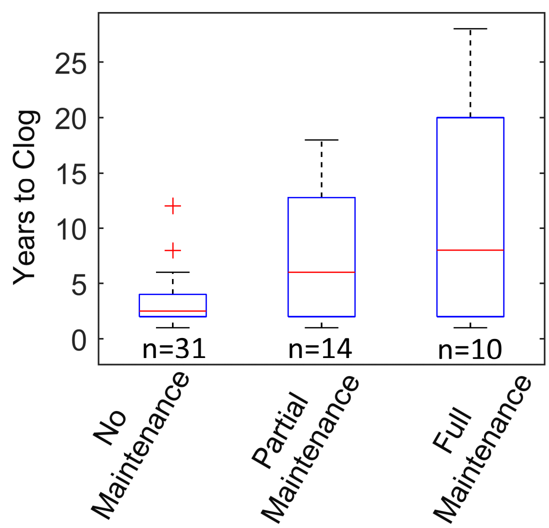

Figure 3. Boxplots of clogging data of permeable pavement under no maintenance, partial maintenance and full maintenance.

Figure 4 shows the empirical cumulative distribution and the gamma distribution of the clogging data for the three maintenance regimes. Here it is important to note that the introduction of maintenance reduces the probability of the SCM clogging. Under no maintenance, there is more than an 80% probability that the SCM will fail in 5 years of functioning. Ideally, the design life for SCMs is expected to be 10-15 years (UDFCD, 2019) and it can be seen that as maintenance is introduced, there is significant variability in performance and the probability that the SCM will clog significant decreases.

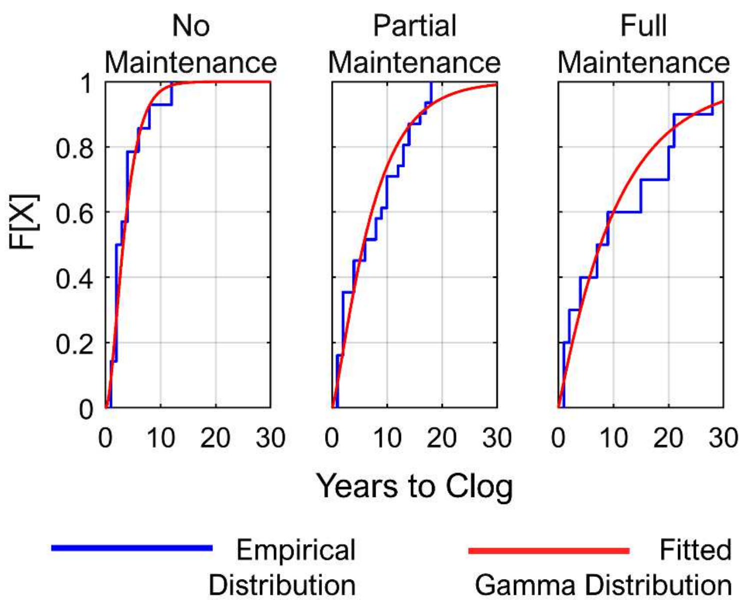

Figure 4. The cumulative distribution function of the clogging data fitted to a gamma distribution for a permeable pavement under no maintenance, partial maintenance, and full maintenance.

It can also be seen that even under full maintenance, SCMs tends to clog over a given period of time and this can be due to issues with technicality of design, construction, change in climate patterns and various other factors (Blecken et al., 2017). For any SCM, due to various highly influential factors contributing to cumulative load, clogging can lead to irreversible decreases in permeability (Blecken et al., 2017; J. A. P. Drake et al., 2013). Regular or periodic maintenance can significantly restore the infiltration capacity of these systems and improve their performance over their design life.

3.2 Sensitivity of Input Parameters

The output variables of interest for the sensitivity analysis were total runoff of the system and the bypass flow leaving the system as overflow due to clogging. Clogging of an SCM is dependent on the impervious areas contributing to stormwater surface runoff. Therefore, the total runoff of the subcatchment and the bypass flow of the SCM were evaluated to conduct sensitivity analysis.

Figure 5 shows the variance decomposition of the first order indices of the 26 input parameters for (1) as total runoff and (2) as bypass flow. For the three maintenance regimes, only a few parameters have high sensitivity index and the remaining parameters have small indices that can be considered insignificant. For total runoff, the parameters that have higher sensitivity index are percentage of imperviousness, capture ratio, minimum infiltration rate and the maintenance regime. These are the input parameters that affect the total stormwater runoff of the subcatchment and it can be seen that the minimum infiltration rate does not influence the bypass response of the SCM. For bypass flow, the significant parameters include percentage of imperviousness, capture ratio and the maintenance regime.

For both total runoff and bypass flow, imperviousness is the most important parameter and as maintenance is introduced, the significance of this parameter decreases. It can also be seen that the significance of capture ratio is greater for the bypass flow when compared to total runoff. Introduction of maintenance also significantly influences the total runoff and bypass flow of the system and it can be seen that for bypass flow, the significance of the maintenance regime is twice as much as it is for total runoff. All the other parameters that were less than 1%

have a sensitivity index of either zero or almost zero having no importance at all and therefore do not influence the performance of the SCM.

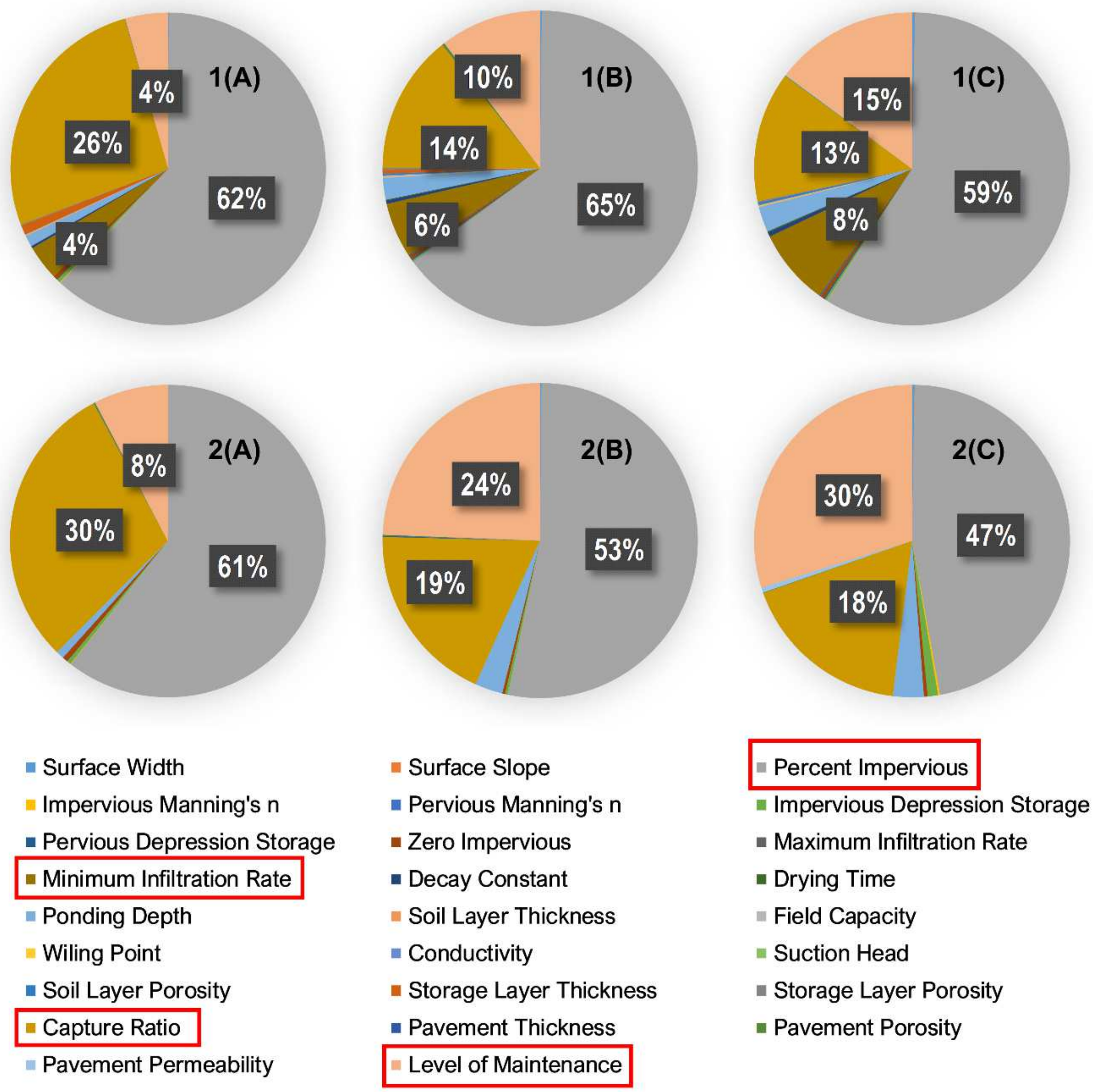

Figure 5. Variance decomposition of the first order sensitivity indices for 1. Total Runoff of the system and 2. Bypass Flow of the SCM under A. No maintenance, Partial Maintenance and C. Full Maintenance.

The first order Sobol indices were then plotted against the total order indices to produce the sensitivity index plots. Figure 6 shows these plots for each of the maintenance regime for total runoff and bypass flow. In these plots, when a 1:1 linear line is drawn, all the parameters are shown above the linear line. The significant parameters are scattered across the top 95% of the space while the non-significant parameters all fail below the 5% space.

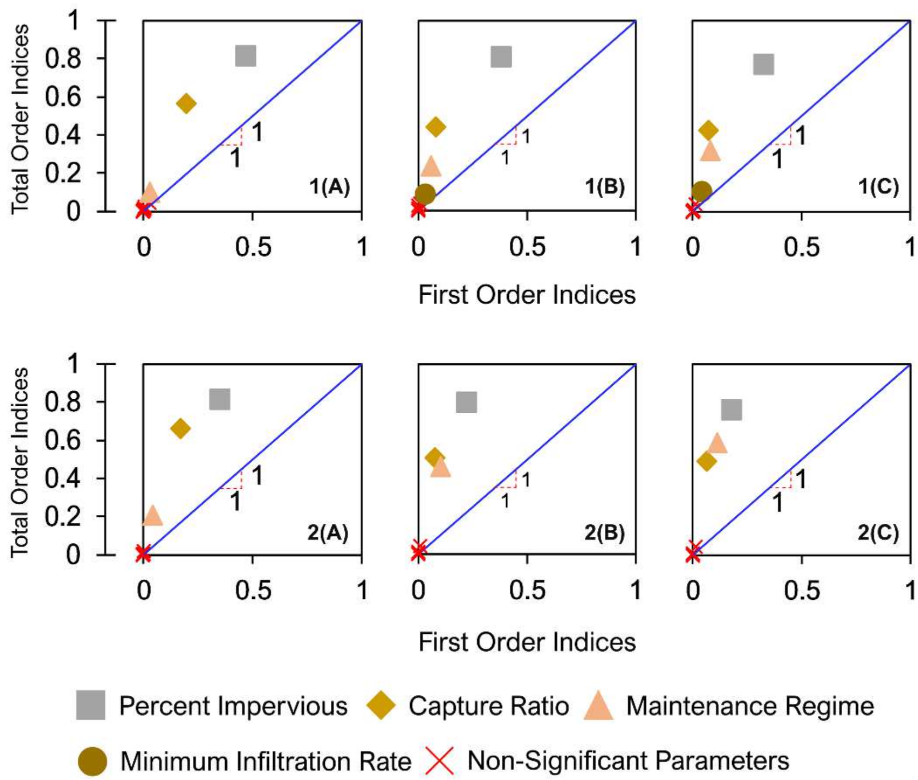

Figure 6. Interaction effects plot of first order vs total order sensitivity indices of 1. Total Runoff of the system and 2. Bypass Flow of the SCM under A. No maintenance, Partial Maintenance and C. Full Maintenance.

This shows that the insignificant parameters fall in the 95% confidence intervals. The remaining parameters outside the confidence intervals are the sensitive significant parameters and need to be carefully considered while designing an SCM. Here we see similar results to that of the variance decomposition charts, we can see that the significant parameters are percent impervious, capture ratio, maintenance regime and the minimum infiltration rate for the total runoff and for bypass flow the important parameters are percent impervious, capture ratio and the maintenance regime. Percent impervious and capture ratio are very important parameters to consider while designing the SCM as they determine the runoff and the load of pollutants of debris coming into the system as stormwater runoff. In SWMM, the clogging potential is determined by the cumulative load of pollutants coming into the system. This also can be attributed the cumulative volume of stormwater runoff produced by the contributing impervious areas.

Previous studies have shown that cumulative inflow of stormwater runoff contributes to the maximum clogging substances (Deo et al., 2010; Lee et al., 2015; Yong et al., 2013). It is very necessary to carefully take into consideration the amount of area being treated by an SCM. Most of the studies reviewed showed that due to improper design in capture ratio where the SCM was not big enough to treat the incoming load of stormwater runoff tend to clog rapidly (Blecken et al., 2017; Siriwardene et al., 2007). Sometimes this also can be due to not having enough storage capacity in the underlying layers. Thus, most of the water is lost from the system untreated and completely violates the purpose of place an SCM.

After identifying the most significant and important parameters, the Monte Carlo simulation was performed again by generating new sample sets. New sample set were generated by keep the non-significant parameters constant for the study region and only the significant parameters such percent impervious, capture ratio, level of maintenance, minimum infiltration rate and surface layer ponding depth were varied. Monte Carlo simulations were run again with 3072 newly generated sample sets and their corresponding outputs were recorded to characterize the response of bypass flow and the role of maintenance over the design life of SCMs.

3.3 Bypass Ratio of SCMs over Time

Figure 7 shows the bypass ratio of the SCM over the entire 30 years under no, partial and full maintenance. It can be seen that the frequency of bypass occurrences increases over time due to clogging for each maintenance regime. For the first three years of functioning, the system has similar performance and between 3 and 5 years, it can be seen that the bypass ratio for the SCM under no maintenance increases rapidly and there is an exponential increase in the frequency of bypass occurrence. This implies that as maintenance is introduced, the frequency of bypass occurrence decreases significantly.

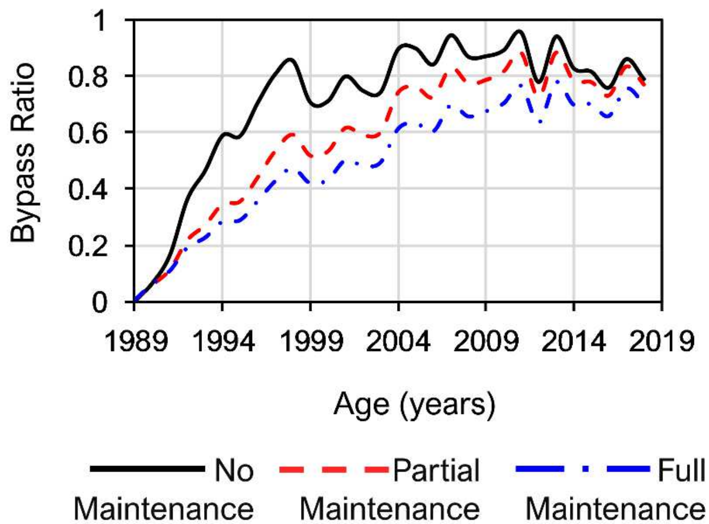

Figure 7. Bypass ratio for no maintenance, partial maintenance, and full maintenance for the assessment period (1989-2018) of 30 years.

Literature suggests that infiltration-based SCMs have the tendency to exponential decrease in the ability to infiltrate the stormwater runoff coming into the system. This mainly occurred between 3 to 5 years of the system being in operation. 15 to 20 years is the general life expectancy for any given SCM. Under no maintenance, the bypass ratio tends to be around 0.85

in just about 10 years. The bypass ratio under partial and full maintenance has a very similar trend and increases gradually over time. The expectation was to see much lesser bypass frequency response under partial and full maintenance. This would help in clearly differentiating the effective response of different maintenance activities, but this result is primarily due to the assumptions made while creating the clogging data based on the type of maintenance activities, land density and the capture ratio.

3.4 Return Level of Bypass Flow

The return levels of bypass intensity (in/hr) and their corresponding return periods were calculated using the GPD. Figure 8 shows the return level as bypass intensity of the SCM for the three different maintenance regimes with their corresponding return period in years. There is a significant difference in the return level between no maintenance, partial maintenance and full maintenance as the return period increases. For the 10-yr return period, the bypass intensity is around 70 in/hr, 85 in/hr and 95 in/hr for no maintenance, partial maintenance and full maintenance, respectively. This shows that there is nearly a 75% decrease in bypass flow intensity of the system between no maintenance and full maintenance. As the return period increases, the difference in intensities of bypass only increases among the different levels of maintenance.

The confidence intervals show the uncertainty for each of the maintenance regimes. There is higher uncertainty under full maintenance and the uncertainty is much lesser for no maintenance. These increased uncertainties under partial and full maintenance shows that there is high variability in the performance of the SCMs and it can be difficult the predict to bypass response for a given return period compared to no maintenance. This corresponds to the assumptions made to categorize the clogging data. Higher uncertainty under full maintenance show that there is reduced bypass overflow and it does not occur as often as it does under no maintenance. This return level plot can be used to make predictions on the reliability of the performance of the SCM based on the bypass response for a given design life period.

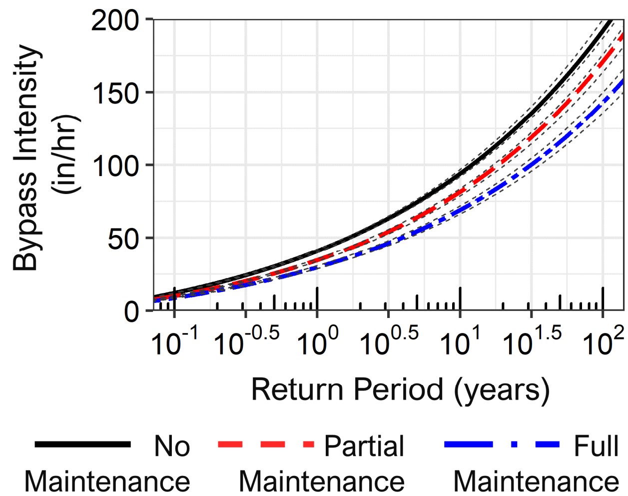

Figure 8. Return Level plot with Return Period in years on the x-axis and the corresponding bypass intensities on the y-axis for the three levels of maintenance with confidence intervals.

3.5 Reliability and Time to Failure

Figure 9 shows the hazard function for the bypass overflow of the SCM under varying maintenance regimes for the assessment period of 30 years. The rate for each level of maintenance follows a bathtub curve which is more skewed to the wear-out-life period. The failure rate tends to go to the wear-out stage in just around 5 years of operation. Under no maintenance, the rate of failure goes over 50% in 7-10 years of operation and this indicates the necessity and importance of appropriate maintenance. For partial and full maintenance, the rate of failure has a more gradual increase, but it can be clearly seen that the failure rate increases exponentially over time. This also shows that under maintenance, the life of the system is prolonged, and the rate of failure is much less rapid when compared to systems with no maintenance at all.

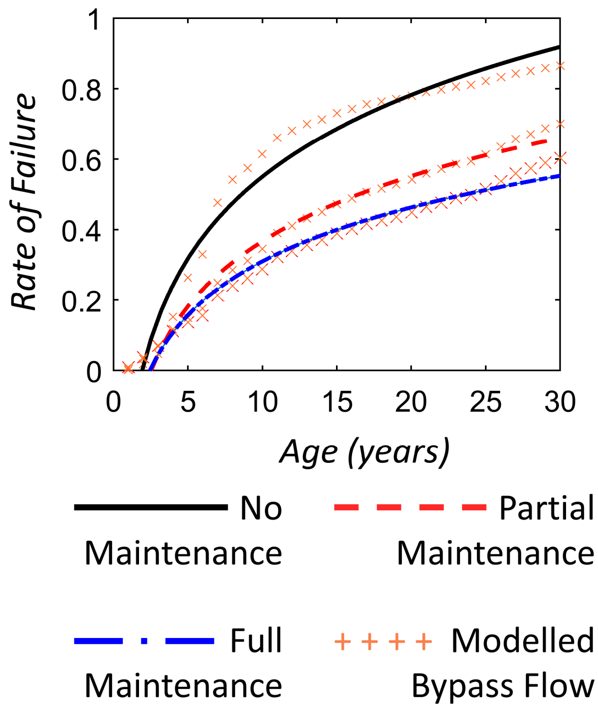

Figure 9. Hazard function of the SCM for the three levels of maintenance assessed for the period of 30 years

Figure 10 shows the hazard function, reliability function and the failure density function for the bypass of the SCM under the three levels of maintenance. The reliability of the SCM under no maintenance drops below 50% in 5 years whereas under partial and full maintenance, there is 75% reliability. The reliability is almost zero under no maintenance in less than 10 years. Partial and full maintenance's reliability drops below 0.5 between 7-8 years of operation and these two scenarios tend to be very close to each other in performance.

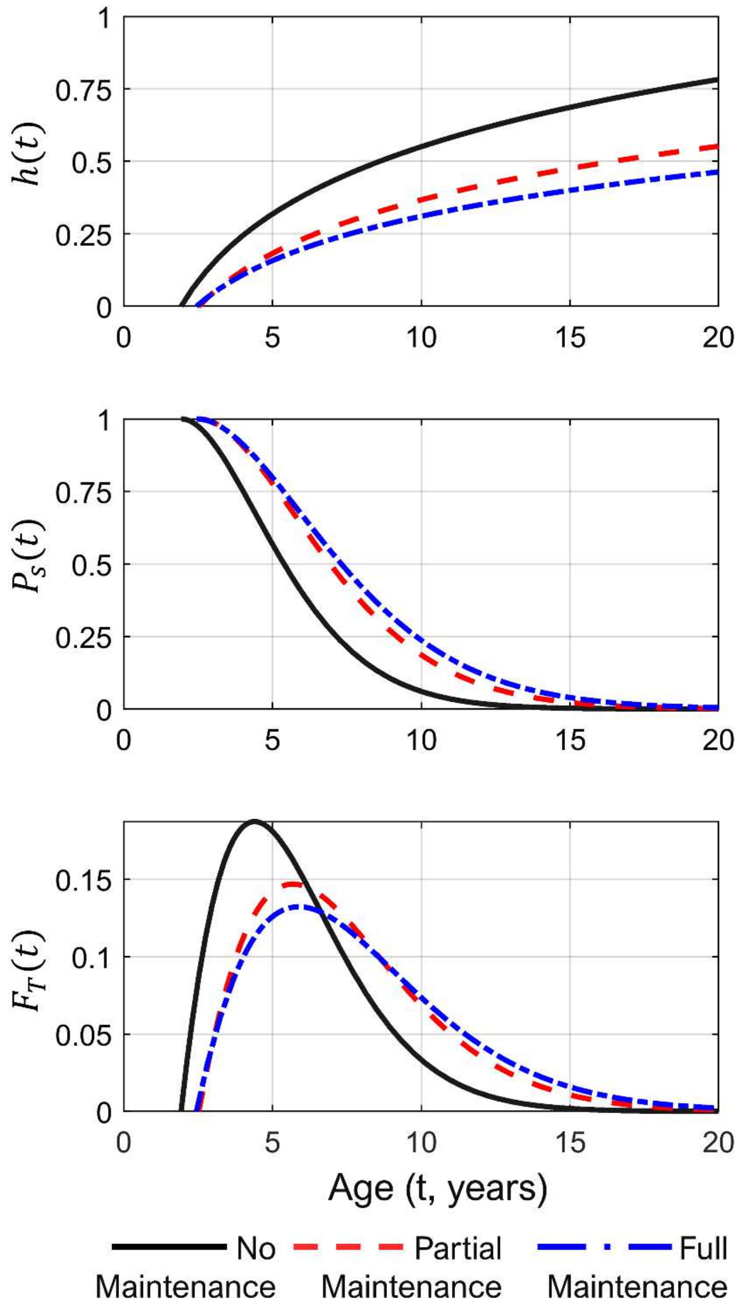

Figure 10. Representation of A. Hazard function or failure rate function, B. Reliability function and C. Failure density function for the three levels of maintenance.

The failure density function which is also the probability density function shows that under no maintenance, the SCM tends to failure in less than 5 years and for partial and full maintenance, the SCM fails in just over 5 years. The mean time to failure or the expected time to failure of the SCM was calculated to be 3.9 years, 5 years and 5.5 years under no maintenance, partial maintenance and full maintenance, respectively. This clearly implies the importance of maintenance, but it is also concerning to understand that even under full maintenance, the SCM has a MTTF of less than 10 years where a SCM is generally designed to perform efficiently for at least 10 to 15 years.

Chapter 4. Discussion

Observing the clogging data of permeable pavements from the last two decades, we can see that the role of maintenance has also become significantly important for better performance of the SCM. Appropriate design and sizing of low impact developments are critical to ensure the system functions according to design. Studies have shown that there have been multiple cases where systems have clogged prematurely due to improper design or depending on the contribution impervious areas (Lee et al., 2015; N. Siriwardene et al., 2007; N. R. Siriwardene et al., 2007).

The bypass ratio shows that introducing maintenance to a SCM can significantly reduce the frequency of bypass occurrences. Significant differences were seen under different maintenance regimes in the return level plot which can help in making prediction of the bypass intensity response of the SCM for a given design life period. One important observation from the analysis was that the response for partial maintenance and full maintenance were very close to each other while no maintenance varied by a significant magnitude. The probable explanation for this could be the assumptions made while characterizing the clogging data. Certain assumptions had to be made based on the capture ratio, land density, and the maintenance activity involved to categorize the age of permeable pavements to no maintenance, partial maintenance, and full maintenance. This can produce a certain amount of uncertainty in the results and while this is true, studies have also suggested that over a period any system is susceptible to irreversible clogging. This can be due to several factors such as wet and dry flows, climate, design issues, and so on.

The rate of failure and time to failure analysis shows that failure or clogging in this case in the SCM follows an exponential trend, especially under no maintenance. A number of studies have shown that any given infiltration-based stormwater system starts to fail somewhere between 3 and 6 years after which there is an exponential decrease in the performance of these systems (Emerson et al., 2010). There is a widespread increase in implementation of SCMs across the world and therefore it is important to guarantee the adequate function of the SCM in both the short and long-term (Blecken et al., 2017).

The idea of implementing SCMs and low impact developments are that they mimic natural hydrologic cycle, reducing the peak runoff volume, providing storage to reduce flooding and the provide water quality benefits by serving as a treatment for stormwater runoff pollutants. But when maintenance is neglected, the investment capital in the design and construction of these systems is wasted. Moreover, failed systems can potentially further damage the existing hydrology of a given watershed. Some of the future options and critical considerations to favor the implementation and use of SCMs have been suggested by various studies.

Recommendations have been made to make sure that SCMs are properly designed by understanding the need in context of the watershed features and the type of runoff treated by these systems (Emerson et al., 2010; Kandra et al., 2015). Necessary attention should be provided while designing and constructing these systems to pore size of underlying aggregates along with the materials used for these aggregate layers as clogging start with these pores capturing untreated pollutant coming into the systems in the stormwater runoff (Deo et al., 2010). A SCM should be designed, constructed and maintained with a factor of safety, for example providing larger surface areas. This can provide additional space for natural physical processes that can allow for partial failure of the SCM should something go wrong (Blecken et al., 2017; Emerson et al., 2010; N. Siriwardene et al., 2007). Implementing these SCMs in locations where is a constant water level have shown to improve the performance and prolong the life of these systems (Siriwardene et al., 2007) and studies have shown that systems that are sized only according to the upstream impervious are may clog prematurely. Most importantly, periodic inspection and regular maintenance is very critical in maintaining the longevity of these stormwater infiltration systems.

One of the limitations of this study was the bias in the assumptions made during collecting and categorizing the clogging data. Over the entire study, the performance of the SCM under partial and full maintenance are relatively close and this is limited mainly by the clogging data collected from previous studies. A larger number of data will provide space for more stringent conditions which categorizing the data which will produce significantly improved results. Future work could include more parameters that might affect the model for example, the influence of climate change. This can be conducted by running the simulations across various climate regions to understand the influence of climate on the performance of SCMs.

Chapter 5. Conclusion

Rigorous global sensitivity analysis identified the important parameters of design to be percentage of imperviousness, capture ratio, and the maintenance regime which are part of the clogging factor parameter in SWMM. It was clearly identified that maintenance directly influences the bypass flow frequency and intensity response of any given SCM. Clogging and maintenance is a major determinant in the performance of a SCM over its design life as suggested by previous studies (Deo et al., 2010; Kandra et al., 2015; Kia et al., 2017; N. Siriwardene et al., 2007). Introduction of maintenance to the SCM show decrease in the frequency of bypass occurrences and an increase in the uncertainty of bypass intensity over their design life. Subsequently, the hazard function analysis shows that failure due to clogging occurs exponentially over time and the reliability of the system increases with introduction of maintenance. The mean time to failure was found to be less than 10 years for the SCM under full, partial and no maintenance regimes. Significant improvement in the performance of SCMs were seen with the introduction of maintenance, comparing no maintenance and partial maintenance regimes. As the interest towards new SCM technology and practices increase among cities and communities, it is important to provide long-term functionality as some of these systems require high capital for construction and maintenance. Regular inspection and maintenance including cleaning components of the SCM, trash and debris removal, vegetation condition, sediment accumulation and standard monitoring of the treatment capacity of these systems are critical in ensuring that these SCMs perform as per design for longer periods of time. Long term maintenance over the design life of the system has to be further researched, especially for onsite practices to be able to advise better on effective design and maintenance of these systems to ensure that they are preserving the hydrological balance and improving the lifestyle of communities.

References

Abbot, C., & Comino, L. (2003). In-situ hydraulic performance of a permeable pavement sustainable urban drainage system. *Journal of Institution of Water and Environmental Management*, *17*, 187–190. https://doi.org/https://doi.org/10.1111/j.1747-6593.2003.tb00460.x

Baladés, J. D., Legret, M., & Madiec, H. (1995). Permeable pavements: Pollution management tools. *Water Science and Technology*, *32*(1), 49–56. https://doi.org/https://doi.org/10.1016/0273-1223(95)00537-W

Blecken, G. T., Hunt, W. F., Al-Rubaei, A. M., Viklander, M., & Lord, W. G. (2017). Stormwater control measure (SCM) maintenance considerations to ensure designed functionality. *Urban Water Journal*, *14*(3), 278–290. https://doi.org/10.1080/1573062X.2015.1111913

Boogaard, F. C., Lucke, T., & Beecham, S. (2014). Effect of Age of Permeable Pavements on Their Infiltration Function. *Clean - Soil, Air, Water*, *42*(2), 146–152. https://doi.org/https://doi.org/10.1002/clen.201300113

Brattebo, B. O., & Booth, D. B. (2003). Long-term stormwater quantity and quality performance of permeable pavement systems. *Water Research*, *37*(18), 4369–4376. https://doi.org/10.1016/S0043-1354(03)00410-X

Brown, R. A., & Borst, M. (2013). Assessment of Clogging Dynamics in Permeable Pavement Systems with Time Domain Reflectometers. *Journal of Environmental Engineering*, *139*(10), 1255–1265. https://doi.org/10.1061/(ASCE)EE.1943-7870

Brown, R. A., & Borst, M. (2014). Evaluation of surface infiltration testing procedures in permeable pavement systems. *Journal of Environmental Engineering (United States)*, *140*(3), 1–12. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000808

Burszta-adamiak, E., & Mrowiec, M. (2013). Modelling of Green roofs ' hydrologic performance using EPA ' s SWMM. *Water Science and Technology: A Journal of the International Association on Water Pollution Research.*, *68*, 36–42. https://doi.org/10.2166/wst.2013.219

Chan, K., Saltelli, A., & Tarantola, S. (1997). Sensitivity Analysis of Model Output: Variance-Based Methods Make the Difference. *Proceedings of the 1997 Winter Simulation Conference*, *ii*, 261–268.

Chopra, M., Kakuturu, S., Ballock, C., Spence, J., & Wanielista, M. (2010). Effect of Rejuvenation Methods on the Infiltration Rates of Pervious Concrete Pavements. *Journal of Hydrologic Engineering*, *15*. https://doi.org/https://www.researchgate.net/deref/http%3A%2F%2Fdx.doi.org%2F10.1061%2F(ASCE)HE.1943-5584.0000117

Coles, S. (2001). *An Introduction to Statistical Modeling of Extreme Values*.

Deo, O., Sumanasooriya, M., & Neithalath, N. (2010). Permeability Reduction in Pervious Concretes due to Clogging: Experiments and Modeling. *Journal of Materials in Civil Engineering*, *22*(7), 741–751. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000079

Drake, J. A. P., Bradford, A., & Marsalek, J. (2013). Review of environmental performance of permeable pavement systems : State of the knowledge. *Water Quality Research Journal of Canada*, *48*. https://doi.org/10.2166/wqrjc2013.055

Drake, J., Bradford, A., Seters, T. Van, & MacMillan, G. (2012). Evaluation of permeable pavements in cold climates–Kortright centre, Vaughan. *Toronto and Region Conservation Authority*. https://scholar.google.co.za/scholar?hl=en&q=Evaluation+of+Permeable+Pavements+in+Cold+Climates+–+Kortright+Centre&btnG=&as_sdt=1,5&as_sdtp=#0

Dreelin, E. A., Fowler, L., & Ronald Carroll, C. (2006). A test of porous pavement effectiveness on clay soils during natural storm events. *Water Research*, *40*(4), 799–805. https://doi.org/10.1016/j.watres.2005.12.002

Duin, B. Van, Brown, C., Chu, A., Marsalek, J., & Valeo, C. (2008). Characterization of Long-Term Solids Removal and Clogging Processes in Two Types of Permeable Pavement under Cold Climate Conditions. *Water Research*, 1–10.

Emerson, C. H., Wadzuk, B. M., & Traver, R. G. (2010). Hydraulic evolution and total suspended solids capture of an infiltration trench. *Hydrological Processes*, *24*(8), 1008–1014. https://doi.org/10.1002/hyp.7539

Erickson, A. J., Taguchi, V. J., & Gulliver, J. S. (2018). The challenge of maintaining stormwater control measures: A synthesis of recent research and practitioner experience. *Sustainability (Switzerland)*, *10*(10), 1–15. https://doi.org/10.3390/su10103666

Fassman, E. A., & Blackbourn, S. (2010). Urban Runoff Mitigation by a Permeable Pavement System over Impermeable Soils. *Journal of Hydrologic Engineering*, *15*(6). https://doi.org/https://doi.org/10.1061/(ASCE)HE.1943-5584.0000238

Feng, K., Lu, Z., & Yang, C. (2019). Enhanced Morris method for global sensitivity analysis: good proxy of Sobol' index. *Structural and Multidisciplinary Optimization*, *59*(2), 373–387. https://doi.org/10.1007/s00158-018-2071-7

Ganji, A., Maier, H. R., & Dandy, G. C. (2016). A modified Sobol' sensitivity analysis method for decision-making in environmental problems. *Environmental Modelling and Software*, *75*(November 2017), 15–27. https://doi.org/10.1016/j.envsoft.2015.10.001

Ghanbari, M., Arabi, M., Obeysekera, J., & Sweet, W. (2019). A Coherent Statistical Model for Coastal Flood Frequency Analysis Under Nonstationary Sea Level Conditions. *Earth's Future*, *7*(2), 162–177. https://doi.org/10.1029/2018EF001089

Ghanbari, M., Asce, S. M., Arabi, M., Asce, M., Obeysekera, J., & Asce, M. (2020). *Chronic and Acute Coastal Flood Risks to Assets and Communities in Southeast Florida*. *146*(7), 1–10. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001245

Gharib, A., Davies, E. G. R., Goss, G. G., & Faramarzi, M. (2017). Assessment of the combined effects of threshold selection and parameter estimation of generalized Pareto distribution with applications to flood frequency analysis. *Water (Switzerland)*, *9*(9). https://doi.org/10.3390/w9090692

Henderson, V., & Tighe, S. (2011). Evaluation of pervious concrete pavement permeability renewal maintenance methods at field sites in Canada. *Canadian Journal of Civil Engineering*, *38*, 1404–1413.

Hou, L., Feng, S., Ding, Y., Zhang, S., & Huo, Z. (2008). Experimental study on rainfall-runoff relation for porous pavements. *Hydrology Research*, *39*(3), 181–190. https://doi.org/10.2166/nh.2008.001

James, W., & Gerrits, C. (2003). Maintenance of Infiltration in Modular Interlocking Concrete Pavers with External Drainage Cells. *Journal of Water Management Modeling*. https://doi.org/10.14796/JWMM.R215-22

Kandra, H., McCarthy, D., & Deletic, A. (2015). Assessment of the Impact of Stormwater Characteristics on Clogging in Stormwater Filters. *Water Resources Management*, *29*(4), 1031–1048. https://doi.org/10.1007/s11269-014-0858-x

Kapur, K. C., & Pecht, M. (2014). *Reliabilty Engineering*.

Kazemi, H., Rockaway, T. D., Rivard, J., & Abdollahian, S. (2017). Assessment of Surface Infiltration Performance and Maintenance of Two Permeable Pavement Systems in Louisville, Kentucky. *Journal of Sustainable Water in the Built Environment*, *3*. https://doi.org/https://www.researchgate.net/deref/http%3A%2F%2Fdx.doi.org%2F10.1061%2FJSWBAY.0000830

Kia, A., Wong, H. S., & Cheeseman, C. R. (2017). Clogging in permeable concrete: A review. *Journal of Environmental Management*, *193*(September), 221–233. https://doi.org/10.1016/j.jenvman.2017.02.018

Kresin, C., James, W., & Elrick, D. (1997). Observations of Infiltration Through Clogged Porous Concrete Block Pavers. *Journal of Water Management Modeling*, *5*. https://doi.org/10.14796/jwmm.r195-10

Lamboni, M., Iooss, B., Popelin, A. L., & Gamboa, F. (2013). Derivative-based global sensitivity measures: General links with Sobol' indices and numerical tests. *Mathematics and Computers in Simulation*, *87*, 45–54. https://doi.org/10.1016/j.matcom.2013.02.002

Lee, J. G., Borst, M., Brown, R. A., Rossman, L., & Simon, M. A. (2015). Modeling the hydrologic processes of a permeable pavement system. *Journal of Hydrologic Engineering*, *20*(5), 1–12. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001088

Link, K. G., Stobb, M. T., Paola, J. Di, Neeves, K. B., Fogelson, A. L., Sindi, S. S., & Leiderman, K. (2018). A local and global sensitivity analysis of a mathematical model of coagulation and platelet deposition under flow. In *PLoS ONE* (Vol. 13, Issue 7). https://doi.org/10.1371/journal.pone.0200917

Niazi, M., Nietch, C., Maghrebi, M., Jackson, N., Bennett, B. R., Tryby, M., & Massoudieh, A. (2017). Storm Water Management Model: Performance Review and Gap Analysis. In *Journal of Sustainable Water Built Environment* (Vol. 3, Issue 2). https://doi.org/10.1061/JSWBAY.0000817

NOAA. (n.d.). *Global Historical Climatology Network, Daily data for Fort Collins for 30 years (1989-2018)*. NOAA/National Center for Environmental Information. Accessed on 9-3-2019. https://doi.org/https://www.ncdc.noaa.gov/data-access

North Carolina Department of Transportation. (2010). Stormwater Control Inspection and Maintenance Manual. *NCDOT - HSP - 2010 - 01*. https://www.ncdot.gov/programs/environment/stormwater/download/SWControlInspectionMaintJan2010.pdf

Park, D., Song, Y. Il, & Roesner, L. A. (2013). Effect of the seasonal rainfall distribution on storm-water quality capture volume estimation. *Journal of Water Resources Planning and Management*, *139*(1), 45–52. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000204

Pezzaniti, D., Beecham, S., & Kandasamy, J. (2009). A laboratory and field investigation into the effective life of permeable pavements. *Proceedings of the Institution of Civil Engineers, Water Management*, *162*, 76–87.

Piza, H., & Rapp, D. N. (2018). *Technical Memorandum on Determination of Runoff Reduction Method Equations (UIA to RPA) based on Multivariable SWMM Analysis. Urban Drainage and Flood Control District: Denver, CO.*

Pratt, C. J., Mantle, J. D. G., & Schofield, P. A. (1995). UK Research into the Performance of Permeable Pavement, Reservoir Structures in Controlling Stormwater Discharge Quantity and Quality. *Wat. Sci. Tech. Vol. 32, No.1, Pp. 63-69*.

Razzaghmanesh, M. et al. (2018). A Review of Permeable Pavement Clogging Investigations and Recommended Maintenance Regimes. *Water*. https://doi.org/10.3390/w10030337

Read, L. K., & Vogel, R. M. (2015). Hazard function analysis for flood planning under nonstationarity. *Water Resources Research*. https://doi.org/https://doi.org/10.1002/2015WR018370

Read, L. K., & Vogel, R. M. (2016). Hazard function theory for nonstationary natural hazards. *Natural Hazards and Earth System Sciences*, *16*(4), 915–925. https://doi.org/10.5194/nhess-16-915-2016

Rootzén, H., & Katz, R. W. (2013). Design Life Level: Quantifying risk in a changing climate. *Water Resources Research*, *49*(9), 5964–5972. https://doi.org/10.1002/wrcr.20425

Roseen, R. M., Ballestero, T. P., Houle, J. J., Briggs, J. F., & Houle, K. M. (2012). Water quality and hydrologic performance of a porous asphalt pavement as a storm-water treatment strategy in a cold climate. *Journal of Environmental Engineering (United States)*, *138*(1), 81–89. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000459

Rosolem, R., Gupta, H. V., Shuttleworth, W. J., Zeng, X., & De Gonçalves, L. G. G. (2012). A fully multiple-criteria implementation of the Sobol' method for parameter sensitivity analysis. *Journal of Geophysical Research*, *117*(7), 1–18. https://doi.org/10.1029/2011JD016355

Rossman, L. A. (2015). Storm Water Management Model User's Manual Version 5.1. *EPA/600/R-14/413b*, *Cincinnati*(September). www2.epa.gov/water-research

Rossman, L. A., & Huber, W. C. (2016). Storm Water Management Model Reference Manual Volume III – Water Quality EPA/600/R-16/093. *United States Environment Protection Agency*. www.epa.gov/water-research

Sadeghi, K. M., Loáiciga, H. A., & Kharaghani, S. (2018). Stormwater Control Measures for Runoff and Water Quality Management in Urban Landscapes. *Journal of the American Water Resources Association*, *54*(1), 124–133. https://doi.org/10.1111/1752-1688.12547

Saeed Far, S., & Abd. Wahab, A. K. (2016). Evaluation of Peaks-Over-Threshold Method. *Ocean Science Discussions*, *July*, 1–25. https://doi.org/10.5194/os-2016-47

Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., & Tarantola, S. (2008). Global Sensitivity Analysis: The Primer. In *John Wiley & Sons, Ltd*. https://doi.org/10.1111/j.1751-5823.2008.00062_17.x

Saltelli, A., Tarantola, S., Campolongo, F., & Ratto, M. (2004). *Sensitivity Analysis in Practice: a Guide to Assessing Scientific Models*. https://doi.org/10.1111/j.1467-985x.2005.358_16.x

Siriwardene, N., Deletic, A., & Fletcher, T. D. (2007). *Application of Laboratory Experiment Results into Practice : Clogging of Stormwater Infiltration Systems*.

Siriwardene, N. R., Deletic, A., & Fletcher, T. D. (2007). Clogging of stormwater gravel infiltration systems and filters: Insights from a laboratory study. *Water Research*, *41*(7), 1433–1440. https://doi.org/10.1016/j.watres.2006.12.040

Sobol, I. M. (1990). On Sensitivity Estimation for Nonlinear Mathematical Models. *Matem. Mod.*, *2*(1), 112–118. https://doi.org/10.18287/0134-2452-2015-39-4-459-461.

Sweet, W. V., Park, J., Marra, J., Zervas, C., & Gill, S. (2014). Sea Level Rise and Nuisance Flood Frequency Changes around the United States. *NOAA Technical Report NOS CO-OPS 073*, *June*, 58. https://doi.org/10.13140/2.1.3900.2887

Toronto Regional and Conservation Authority. (2008). Performance Evaluation of Permeable Pavement and a Bioretention Swale. *Seneca College, King City, Ontario*.

Tung, Y., Yen, B.-C., & Melching, C. S. (2006). *Hydrosystems Engineering Reliability Assessment and Risk Analysis*.

Urban Drainage Flood Control District (UDFCD). (2019). *Urban Storm Drainage Criteria Manual Volume 3. Stormwater Quality*.

Wan, H., Xia, J., Zhang, L., She, D., Xiao, Y., & Zou, L. (2015). Sensitivity and interaction analysis based on Sobol' method and its application in a distributed flood forecasting model. *Water*, *7*(6), 2924–2951. https://doi.org/10.3390/w7062924

Wang, J., Forman, B. A., & Davis, A. P. (2018). Probabilistic Stormwater Runoff and Water Quality Modeling of a Highway in Suburban Maryland. *Journal of Hydrologic Engineering*, *23*(2), 1–12. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001600.

Winston, R. J., Al-Rubaei, A. M., Blecken, G. T., & Hunt, W. F. (2016). A Simple Infiltration Test for Determination of Permeable Pavement Maintenance Needs. *Journal of Environmental Engineering (United States)*, *142*(10), 1–5. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001121

Winston, R. J., Al-Rubaei, A. M., Blecken, G. T., Viklander, M., & Hunt, W. F. (2016). Maintenance measures for preservation and recovery of permeable pavement surface infiltration rate - The effects of street sweeping, vacuum cleaning, high pressure washing, and milling. *Journal of Environmental Management*, *169*, 132–144. https://doi.org/10.1016/j.jenvman.2015.12.026

Xiao, Q., & McPherson, E. G. (2011). Performance of engineered soil and trees in a parking lot bioswale. *Urban Water Journal*, *8*(4), 241–253. https://doi.org/10.1080/1573062X.2011.596213

Yan, L., Xiong, L., Guo, S., Xu, C. Y., Xia, J., & Du, T. (2017). Comparison of four nonstationary hydrologic design methods for changing environment. *Journal of Hydrology*, *551*, 132–150. https://doi.org/10.1016/j.jhydrol.2017.06.001

Yong, C. F., McCarthy, D. T., & Deletic, A. (2013). Predicting physical clogging of porous and permeable pavements. *Journal of Hydrology*, *481*, 48–55. https://doi.org/10.1016/j.jhydrol.2012.12.009