Modeling the Impact of Climate Change on Stormwater Infrastructure: Application to the Elmhurst, IL

BY

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

List of Abbreviations or nomenclature

ACM	Antecedent Moisture Condition
ANN	Artificial Neural Network
AOGCM	Atmosphere-Ocean General Circulation Modes
CN	Curve Number
DCM	Delta Change Method
EPA	US Environmental Protection Agency
FFEBP	Feed-Forward error back-propagation method
GCM	Global Climate Models/ General Circulation Model
GEV	Generalized Extreme Value
GHG	Green House Gases
GI	Green Infrastructure
GIS	Geographic Information System
GRNN	The Generalized Regression Neural Network
HEC-HMS	Hydrologic Engineering Center- Hydrologic Modeling System
HRU	Hydrologic Response Unit
IDF	Intensity- Duration Frequency
IDOT	Illinois Department of Transportation
IPCC	Intergovernmental Panel on Climate Change
LP(III)	Log Pearson type III
MWRD	Metropolitan Water Reclamation District of Greater Chicago
NARCCAP	North American Regional Climate Change Assessment Program
NCEP-DOE	National Center for Environmental Prediction-Department of Energy
NOAA	National Oceanic and Atmospheric Administration

NRCS(SCS)	Natural Resources Conservation Service (Soil Conservation Service)
PCSWMM	Personal Computer Storm Water Management Model
PWM	Probability Weighted Moments
RCM	Reginal Climate Model
RFA	Regional Frequency Analysis
SCS	Soil Conservation Service
SWAT	Soil and Water Assessment Tool
SWMM	Storm Water Management Model
XPSWMM	Stormwater and Wastewater Management Model

Abstract

The main purpose of this dissertation is to assess and simulate the impact of climate change on stormwater infrastructure for the city of Elmhurst, Illinois. For this research, the Regional and Global Climate Model provided by NARCCAP and based on the HRM3-GFDL dataset are used to project future rainfall patterns. From the dataset, the 3-,6-,12-, and 24-hour rainfall data were extracted for the annual maximum rainfall depths. The annual maximum rainfall data were then used to determine new Intensity-Duration-Frequency (IDF) curves for different recurrence intervals using three different distributions: Log Pearson type III (LP(III)), Generalized Extreme Value (GEV), and Gumbel. Moreover, these new IDF curves were compared with current IDF curves available in the Illinois Bulletin 70 and NOAA Atlas 14.

Hydrological modeling was then performed to evaluate the impact of climate change on the existing drainage system of Elmhurst with conceptual improvements in pipe sizes according to today's rainfall standards (Illinois Bulletin 70). Specifically, the XPSWMM model was used to simulate peak flowrates and runoff volumes. The maximum flowrate was then used to estimate the required new size of the conveyance system. In the last part of this research, the performance of Green Infrastructure on stormwater management was evaluated using the HEC-HMS simulation platform.

Overall, the results suggest that rainfall depth may to increase due to climate change and that current stormwater infrastructure capacity may need to be increased to be able to handle more severe rains. It also determined that Green Infrastructure performs better for relatively small rainfall depths (less than 3 inches) with relatively short duration (about 1-3 hours).

1. Introduction

As the number and severity of extreme storms are increasing the general public is getting more aware of climate change and its damages to social and technical infrastructure systems (Siekmann and Siekmann 2015).

Neuman and Smith (2010) declared that "Cities and infrastructure have always been mutually interdependent and coevolutionary. In fact, cities could not exist without infrastructure." This point was further reinforced by Derrible (2017a, 2017b) more recently. In urban planning, infrastructure has been defined as "above and underground built facilities and networks that provide necessary urban service, which includes publicly and privately-owned providers of systems such as utilities (i.e. gas, electricity, water supply); public works (i.e. roads and bridges, dams and canals); and telecommunications (i.e. Internet, television, satellite)" (Neuman and Smith 2010). The concept of Green Infrastructure (GI) stands in opposition to gray or traditional built infrastructure. As defined by Keeley (2011): "Green infrastructure refers to vegetation, soils, and bioengineered system which provide ecological services such as microclimate regulation, air quality improvements, habitat provision, stormwater management, and aesthetic amenities". However, practically Green infrastructure cannot be counted as flood control facility.

Climate change can significantly impact the water cycle. Some predictions show an increase in maximum discharge due to an increase in annual maximum precipitation and more intense rainfall in the future (Mailhot and Duchesne 2010). Change in rainfall pattern and depth would have effects on urban drainage systems, leading to an increase in the frequency of flooding on the one hand, and in water shortage on the other hand.

Accordingly, an increase in intensity and/or frequency of extremes storm events may lead to increase in sewer overflow and flooding. In urban areas, cities need to come up with strategies to adapt to climate change. Climate adaptation strategies are important to decrease the risk of flooding and maintain an acceptable level of service for current and future infrastructure services, notably because of the significant costs related to socioeconomic damages and flood-related maintenance (Mailhot and Duchesne 2010).

Current stormwater system designs rely on statistical analyses of past extreme precipitation, and generally do not account for the impact of climate change. Nevertheless, besides changes in receiving water level, modeling capacities, urban planning, and environmental considerations should be considered for stormwater system design improvement. In fact, it is important to identify/estimate the full possible impacts related to climate change within the technical lifetime of an urban infrastructure system (Arnbjerg-Nielsen 2011).

In general, an increase in impervious area linked with urbanization leads to a decrease in rainwater infiltration, thus magnifying hydrological effects. Moreover, changes in landcover can result in an increase in volume, discharge, and frequency of floods in the future. Consequently, urban water systems can be seriously affected by climate change, especially in urban areas such as in the case of the City of Elmhurst, Illinois, located in northeastern Illinois.

1.1 Objective

Arnbjerg-Nielsen (2011) defined urban drainage as “a relatively old interdisciplinary engineering field” and he stated that “most of the design rules for urban conveyance system are based on practices rather than the development of a scientific method”. Nonetheless, climate change often leads to an increase in uncertainty when it comes to stormwater management and revisiting current practices may be necessary. In addition, current design practices rely on the analysis of historical data as opposed to forecasted data that take into account climate change. As a result, even though the use of hydrological models helps designers evaluate stormwater infrastructure designs, they should still consider the meteorological changes in their designs (Thakali, Kalra, and Ahmad 2016).

This dissertation contains two parts. In the first part, a detailed statistical analysis of a future projected climate model dataset is presented. This dataset consists of a 3-hour rainfall data for northeastern Illinois for the period 2038-2070, projected by the North American Regional Climate Change Assessment Program (NARCCAP). The analysis utilizes three different types of statistical distributions: 1) Generalized Extreme Value (GEV), 2) Log Pearson type III (LP(III)), and 3) Gumbel distributions to find the best fit for the dataset. Then, the results of the analysis were compared to previous studies in the region using older rainfall datasets, including the Illinois Bulletin 70 (1901-1980) and the NOAA Atlas 14 (different time periods). The second part of this dissertation contains hydrological simulations for a site located in the city of Elmhurst, IL. In this second part, runoff from the site was computed for current rainfall data and using future climate estimations. Then, the results of the simulation were compared to the rainfall data results from the Illinois Bulletin 70 (the current controlling standard for northeastern Illinois).

The overall objective of this dissertation is to estimate future rainfall patterns for the City of Elmhurst and to simulate the impact of climate change on the current stormwater conveyance system. The following steps are followed in this study:

1. Obtain and screen rainfall data from the climate model;
2. Fit the appropriate probability distribution to data.;
3. Provide revised Intensity-Duration-Frequency (IDF) curves;
4. Compare the computed rainfall to the Illinois Bulletin 70 and NOAA Atlas 14;
5. Simulate the runoff from the estimated rainfall;
6. Compare the simulated runoff with the Illinois Bulletin 70;
7. Compute the impact of GIs (i.e., permeable pavement and green roofs) on peak flowrate and runoff volume.

This study used statistical analysis to project rainfall data for 3-, 6-,12- and 24-hour storm duration; and 2-, 5-, 10-, 25-, 50- and 100-years recurrence intervals from the climate model. An annual maximum series was used. The annual maximum series accounts for the largest events in each calendar year. A linear regression method was used to estimate rainfall data for 1- and 2- hour for the 100-year recurrence interval. The 1-, 2- and 3-hour rainfall data were used for simulating runoff from the study site.

2. Literature Review

This section will discuss previous studies on historical changes on extreme rainfall, future climate changes, and projected climate models. Also, a brief review of different hydrological models will be presented.

2.1 Historical change in precipitation extremes

Urbanization generally leads to an increase in impervious areas, which lead to a decrease in rainwater infiltration, which in turn can generate significant hydrological impacts. In particular, changes in land cover related to urbanization have generally resulted in an increase in discharge, volume, and frequency of floods. According to different climate projection results, there would be higher intensity in rainfall event followed by drought period (Mailhot and Duchesne 2010).

Existing criteria for the design of stormwater management facilities use historical precipitation data by assuming that the probability distribution of extreme rainfalls remains statistically unchanged. This method does not account for the impact of climate change on future meteorological conditions, while historical data indicate that over a 100-year period, substantial changes have occurred.

Karl and Knight (1998) had observed a 10% increase in total annual precipitation in the United States (US) since 1910. Moreover, more than half (53%) of the increases relate directly to both the recurrence and the intensity in the top 10% of the daily rainfall distribution. Groisman et al. (2005) observed changes in intense rainfalls for over half of the total land area over the globe, and they established that both the practical evidence from the period of observation and projected models of greenhouse gases show an increasing probability of intense precipitation events for the US.

Fowler and Kilsby (2003) determined changes in design storms of 1-, 2-, 5-, and 10-day durations from 1961 to 2000 in the United Kingdom (UK). They used regional frequency analysis to determine changes in precipitation patterns.

Madesn and Figdor (2007) systematically analyzed trends from 1948 to 2006. Their study found statistically significant increases of 30% in the recurrence of the intense storm in Washington State and 45% in the Seattle-Tacoma-Bremerton area. In contrast, trends in adjacent states had statistically significant decreases of 14% in Oregon and about 1% increase in Idaho.

Rosenberg et al. (2010) found changes in extreme precipitation frequency distribution in three major metropolitan areas: Puget Sound region (WA), Vancouver (WA), and Spokane(WA). The study showed substantial differences in extreme precipitation trends among different areas over the past 50 years (1949-2007), such as significant increases in 24-hour duration in Puget Sound, non-significant negative changes in Vancouver, and mixed results in Spokane.

2.2 Future projection precipitation extremes

The Intergovernmental Panel on Climate Change (IPCC) indicated that recent anthropogenic activities lead to observable climate changes through the twentieth century and are expected to contribute to future changes in the twenty-first century and beyond, although the proper mechanisms are not clear (“IPCC The Third Assessment Report” 2001; He et al. 2011).

Shaw (2005) studied the consequences of an increase in precipitation on stormwater systems in central New Zealand, by defining low, medium, and high climate change scenarios based on projections of temperature and 24-hour events.

Mailhot et al. (2007) indicated the probability of occurrence of an intense rainfall due to an increasing concentration of greenhouse gases (GHG), which further substantiate the need to revise stormwater system design criteria. The study proposed that current criteria increase the probability of increased flooding due to an increase in the frequency and intensity of extreme events.

Jung et al. (2015) developed a method for forecasting future short-duration precipitation intensity and examined the effect of climate change on urban runoff in the Gunja Drainage Basin in South Korea. The results indicated that there was a significant upward trend in 1-hour and 24-hour durations. They also observed that the simulated peak discharge from their hydrological model increased in short duration rainfall.

Tavakoli and De Smedt (2012) indicated potential effects of climate change on streamflow and soil moisture in the Vermilion basin, IL. The results of the hydrological computation show that the basin may see a reduction in streamflow due to lower soil moisture as a result of a decrease in precipitation in the summer, accompanied by an increase in evaporation.

Emori and Brown (2005) classified the ‘dynamic’ and ‘thermodynamic’ elements of the mean intense rainfall variations projected in six climate model analyses. They also defined the difference between dynamic and thermodynamic as “dynamic changes are related to changes in atmospheric motion, while the thermodynamic change is due to change in atmospheric moisture content”. The thermodynamic changes will have some increases and reductions, in terms of extreme precipitation. Moreover, the dynamic terms play secondary role in making different between mean and extreme precipitation.

2.3 Future climate projections Models

To project climate patterns over long term horizons, a variety of Global Climate Model (also known as General Circulation Models) were developed under different pre-determined greenhouse gas emission scenarios. General Circulation Models (GCM) outputs usually have a horizontal resolution of about 300 km. GCMs are being used to evaluate the impact of climate change, such as projected climate data from Global Climate Models (GCM), which are available in gridded datasets. To utilize CGM outputs in regional studies, dynamic downscaling such as Reginal Climate Models (RCM), and statistical Downscaling were developed.

Karamouz et al. (2011) used a methodology to compute floodplain extent in the Kajoo River in southeastern Iran and the impact of climate change on projected rainfall pattern by using the statistical downscaling method to project rainfall from GCM outputs. The results from different rainfall run-off models indicate that the impact of climate change on urban runoff would lead to the extent of the floodplain in urban areas.

The North American Regional Climate Change Assessment Program (NARCCAP) produces different models of climate data based on nesting techniques within the synoptic-scale GCM on one hand and the related meso-scale spatial and temporal resolution fields simulated by RCMs on the other hand. Even though GCMs are valuable predictive tools, they still possess some limitations; for example, they fail to account properly for certain “multiplier effects,” limitation in computing the power frequently results, imperfections in the models prevent proper simulation of important element of climate change, etc.(Lupo et al. 2013).

Another method to retrieve more disaggregated future climate data is downscaling, which is a process to drive climate projections and it consists of a variety of methods. Downscaling can be done based on spatial and temporal aspects of climate projections. Generally, there are two kinds of downscaling approaches, “statistical downscaling” and “dynamical downscaling.” and they are usually applied to connect the estimated climate outputs to a desired catchment-level hydrological aspect of climate change effects (Thakali, Kalra, and Ahmad 2016). Dynamic downscaling relies on using a RCM, while statistical downscaling relies on historical and/or current largescale atmospheric and local climate variables.

One of the downscaling methods is the Delta Change Method (DCM). DCMs are used as a replacement for other complex downscaling techniques, for gridded future climate data to point-precipitation. This method calculates the deviation between gridded projected future and historic precipitation. In DCMs the historic rainfall data is converted to the point historic precipitation.

Another method uses Artificial Neural Networks (ANN) that can capture non-linear dynamics, although they are generally harder to interpret. This method is extensively used in water resource articles (He et al. 2011; Liu et al. 2017). This model can be used for river forecasting, groundwater problems, and to estimate suspended sediments.

Moreover, ANN can be used to model the rainfall-runoff relationship, which can be combined with either Feed-Forward Error Back-Propagation method (FFEBP) or with the Radial Basis Function to train neural networks. Cigizoglu (2005) used a Generalized Regression Neural Network (GRNN) for seasonal river flow forecasting and calculation, which indicated that the GRNNs were superior to FFEBP in terms of selected performance criteria.

2.4 Hydrological modeling

Hydrological simulation models are commonly utilized in practice to analyze and/or design urban stormwater facilities. A better understanding of hydrologic processes and an improvement in computational speeds further lead to an increase in the suitability of using this computer models.

Some of the concerns related to modeling the effects of climate change on hydrology include modeling uncertainty, topographical factors affecting hydrological responses to climate change and hydrological variability (Praskievicz and Chang 2009). Hydrologic models can be applied to analyze and design stormwater management facilities and to measure the effects of climate change. Hydrologic models use precipitation inputs as event-base data or continuous time-series data.

In urban areas, some of the most significant potential impacts of climate change are those related to stormwater management. The combination of high-intensity precipitation related to climate change and more impervious areas associated with urban development leads to a significant increase in surface runoff and can create flashy storm discharge. Many off-the-shelf models exist to assess these impacts, and they are often developed either by governmental institutions, engineering consulting companies, regulatory authorities, and academic institutions.

Arnold et al. (2012) used the SWAT program (Soil and Water Assessment Tool) to simulate all related processes affecting sediments, water quality, and nutrient leads in catchment. The SWAT model was calibrated to monitor one of the major rivers in Switzerland (Thur River Basin), which is a direct tributary to the Rhine river. This study indicated that SWAT can be used as a transport and flow simulator in small scale watersheds.

The water resource model Personal Computer Storm Water Management Model (PCSWMM), which is the enhanced version of EPA SWMM was used by Praskievicz and Chang (2009) coupled with synthetic climate change projections. They established that "the management action needed to maintain peak discharge at current levels under a 15% increase in rainfall intensity in an urban area in basin Ontario." The effective methods were downspout disconnection, increased depression storage, and increased street detention storage. To successfully adapt to climate change, sustainable stormwater management techniques are likely to become increasingly necessary.

An additional outcome of the raised flashiness of urban runoff following from higher-intensity rainfall and larger impervious areas is that dry seasons may become more critical. The increase in runoff volume and reduction in groundwater recharge correlated to climate change and urban development scenarios not only involve more flooding, but they can also lead to an increase in frequent and critical desiccation due to the decrease in water storage. Fowler, Kilsby, and Stunell (2007) applied the Mospa water management module, operated by the HadCM3 Global Climate Model, to estimate the impacts of climate change on the water supply system of northwestern England. The results showed that the overall possible yield in water may be reduced by 18%; however, the current water infrastructure and management practices should be appropriate to satisfy the expected demand.

2.5 Stormwater Management Models

The role of urban growth on hydrological dynamics should be taken into account in the design of large basins. To achieve the objective, it is necessary to have an arrangement of interrelated models covering the following domains: 1) change in land use, 2) urban drainage, 3) rainfall-runoff (Hutchins et al. 2017). Choosing of a model depends on complexity, available resources, and modeling objectives. In the following section, some common hydrologic models are described.

2.5.1 Stormwater Management Model (SWMM)

The Stormwater Management Model (SWMM) developed by the US Environmental Protection Agency (EPA) is known as one of the best urban runoff models used to simulate hydrological processes in a watershed (Rosner, Aldrich, and Dickinson 1988). To run a simulation in SWMM, the required parameters for predicted climate scenario for different rainfall durations and return periods include topography, soil, conduit, and climate data.

SWMM uses a variety of computational methods, including Unlimited Number of Components, Curve Number infiltration (NRCS (SCS) Curve Number), Integration of Routine Methods, Consist Treatment of Node Flooding, Numerical Stability for Dynamic Wave Routing, and Flexible Real-Time Control Options.

2.5.2 Soil and Water Assessment Tool (SWAT)

SWAT is a physically based distributed hydrological model. It outlines a watershed based on a Hydrologic Response Unit (HRU) that signifies a combination of land use types, soil types, and topography. SWAT Simulation outlines a complete physical water nutrient cycle processes, containing evapotranspiration, infiltration, irrigation, runoff, snowmelt, and groundwater system (Zhang et al. 2017)

SWAT is based on a daily time step and is created to project the impact of land use to manage water sediment and agricultural chemical yield in an ungauged watershed. The water balance is behind the method because it can impact plant growth, movement of sedimentation, pathogens, pesticides, and nutrients. SWAT is able to read observed data directly from files or generate simulated data from observed monthly statistics (Bouslihim et al. 2016; Arnold et al. 2012).

However, Liu et al. (2017) mentioned that "SWAT is a complex model and relatively more difficult to use than simpler models. It also, requires extensive input data, which may not be readily available in the watershed under consideration". Lack of data may also affect simulation results.

2.5.3 Hydrologic Engineering Center- Hydrologic Modeling System (HEC-HMS)

HEC-HMS is designed to compute watershed systems with capability to be suitable in a broad range of geographic areas. This covers wide river basin water supply, and flood hydrology to small urban or natural watershed runoff (Scharffenberg and Mattew J. 2010).

HEC-HMS model includes two types of components to simulate the hydrologic response: 1) primary model components, and 2) input data components. The primary model components are basin models, meteorological models, and control specifications. Data segments like time-series data, paired data, and gridded data are often required as parameter or boundary conditions in basin and meteorological models (Ackerman, Fleming, and Brunner 2008).

A simulation run contains a basin model, meteorological model, and control specifications. Simulation results cover information about peak flow, total runoff volume, and other variables (Zeng et al. 2012). Moreover, time-series table and graphs are available for basin's elements.

2.5.4 Stormwater and Wastewater Management Model (XPSWMM)

The XPSWMM model is "a fully dynamic hydrologic modeling software that combines 1D calculation for upstream to downstream flow with 2D Overland flow calculation." This software's ability includes combining the analysis of flow, sedimented pollution, and design. The XPSWMM applies to floodplain management and river system, wastewater and combined sewer system, and stormwater management.

The XPSWMM module includes 1D and 2D analysis. The 1D analytical engine of XPSWMM is based on the EPA SWMM model, but with the capability to analyze different types of flow in the same run. To improve the accuracy of the analysis, the model has the ability to be integrated with GIS, AutoCAD, and EPA SWMM5. To compare results from different scenarios, the model is capable to run different scenarios simultaneously and provide a comparison graph and separate output files. The special application of this software includes braided river stream, wastewater, and combined sewer management, evaluation planning, national flood insurance planning, and sustainable drainage analysis.

3. Study Area and Data

The scope of this study is to analyze the resilience of an existing stormwater infrastructure system along with conceptual drainage improvements (relief sewers and flood storage) that were sized using Bulletin 70 rainfall, by taking into account more severe storms due to climate change. In this dissertation, the effects of change in precipitation and soil moisture on peak flowrate and runoff volume were analyzed by using XP SWMM model.

3.1 Study Area

The study area in this dissertation is the Crestview Park basin located in the City of Elmhurst, DuPage County, IL. The 180 acres (0.73 km^2) site is situated in the Des Plaines River Watershed and more specifically in the Addison Creek subwatershed. The study area includes part of Arlington Cemetery, and some residential and commercial buildings. The simulation model includes most of the storm sewers and the manholes located next to storage facilities in the area. The overland flow routes are also simulated in the model. Figure 1 shows the overview of site location.

More specifically from Figure 1, the model includes all storm sewers and manholes inside of the entire Crestview Park subbasin. It also contains all the stormwater facilities in the described area. The scope of this model consists of developed areas. The combination of different types of land use can provide an opportunity to indicate the impact of such land uses in future run-off and streamflow in addition to the effect of soil moisture on runoff volume.

Figure 1 Overall View of Crestview Park Basin and Subbasins by GIS.

The study watershed was developed before the issuance of the stormwater management ordinance that requires sufficient detention storage and properly sized overland flow routes. Accordingly, the existing storm sewers were designed prior the development of Bulletin 70 and have an effective capacity to handle between 2- and 5-year storms.

To simulate the impacts of climate change on the amount of generated runoff, XP SWMM was utilized. The Illinois Bulletin 70 design storm depth was used for the baseline model to simulate the current hydrologic performance of the site. Finally, projected climate data was used to simulate the future response of the site by considering different scenarios for development. This section details elements of the study.

3.2 Data collection

In this study, projected and historical precipitation data were downloaded from the NARCCAP website. NARCCAP "provides scientific models with different scenarios which cover northern Mexico, the 48 contiguous United states, most of Canada, and waters of the Atlantic and Pacific oceans next to them" (Mearns et al. 2009). This dataset provides different types of RCMs along with various Global Climate Models (GCM) drivers. The NARCCAP provides different combinations of RCM boundaries and driving models to cover separate and combined uncertainties in the simulated climate change scenarios. Table1 describe the different combination of RCM and driving models.

Table 1 Combination of different Regional Climate Models and Global Climate Models in NARCCAP

Model Combination	Regional Climate model	Global Climate Model Driver
CRCM/CCSM	Canadian Regional Climate Model	Community Climate System Model
CRCM/CGCM3	Canadian Regional Climate Model	Third Generation Coupled Global Climate
ECP2/GFDL	Experimental Climate Prediction Center	Geophysical Fluid Dynamics Laboratory GCM
ECP2/HadCM3	Experimental Climate Prediction Center	Hadley Center Coupled Model version 3
HRM3/HasCM3	Hadley Regional Model version 3	Hadley Center Coupled Model version 3
HRM3/GFDL	Hadley Regional Model version 3	Geophysical Fluid Dynamics Laboratory GCM
MM5I/HadCM3	MMS- PSU/NCAR mesoscale model	Hadley Center Coupled Model, version 3
MM5I/CCSM	MMS- PSU/NCAR mesoscale model	Community Climate System Model
WRFG/CCSM	Weather Research & Forecasting Model	Community Climate System Model
WRFG CGCM3	Weather Research & Forecasting Model	Third Generation Coupled Global Climate
RCM3/CGCM3	Regional Climate model version 3	Third Generation Coupled Global Climate
RCM3/GFDL	Regional Climate model version 4	Geophysical Fluid Dynamics Laboratory GCM
Timeslice/GFDL	-	Geophysical Fluid Dynamics Laboratory GCM
Timeslice/CCSM	-	Community Climate System Model

The climate projection program includes two major phases: in phase I, the six RCMs were simulated by using National Center for Environmental Prediction/Department of Energy (NCEP-DOE) Reanalysis II boundary condition for 25 years (1980-2004). In phase II, Atmosphere-Ocean General Circulation Modes (AOGCMs) boundary conditions were used for the six RCMs in a 30-year period of observed climate (1971-2000) and a 30-year period for future projections (Mearns et al. 2009).

Consequently, for this dissertation, results from HRM3-GFDL were preferred to extract climate data. The results from HRM3-GFDL are reported as both daily or 3-hour reports. Both observed and future precipitation data for the City of Elmhurst were used in this study.

4. Methodology

A set of approaches is utilized in this research. First, a Regional Frequency Analysis (RFA) method based on Generalized Extreme Value (GEV) distribution was used to calculate the design storm depth (i.e., 100 year – 12 hour) from the NARCCAP database. The existing XP SWMM model of the site was then used to measure the effects of climate change on stormwater facilities.

A Python code was developed to aggregate the NARCCAP climate data to 3-, 6-, 12- and 24-hour precipitation. After extraction and screening the results, the data was sorted in descending order. Then annual maximum rainfall depths were calculated for the 3-, 6-, 12- and 24-hour storm durations. The Log Pearson Type III, GEV, and Gumbel distributions were used to calculate new 100-year event rainfall depths for each rainfall durations. Then the calculated 100-year rainfalls were used to estimate the amount of runoff.

The XP SWMM simulation platform was used to simulate the impact of climate change on the peak flowrate and runoff volume generated for different storm duration 100-yr events. First, as a baseline, the model was run with the current design precipitation depth as provided by the Illinois Bulletin 70 reports. The calculated extreme rainfall depths were used to estimate future runoff from the site. In this research the rainfall distribution is assumed to be equivalent for current and future design storms (i.e., Huff first quartile). Tavakoli and De Smedt (2012) indicated that climate change would have effects on decreased soil wetness by 30%. Accordingly, soil moisture reduction was considered in future storm event runoff simulation.

4.1 Statistical analysis of Rainfall Data

Due to limited available observed precipitation data, many theoretical probability distributions have been used to estimate rainfall data magnitudes for large return periods. A short description of Log Pearson Type III, Gumbel and Generalized extreme value distribution are presented.

4.1.1 Log Pearson Type III distribution

The Log Pearson type III uses the logarithm of the rainfall data values by using three parameters as mean and standard deviation calculated from logarithmically transformed data, and skewness coefficient (Chow, Maidment, and Mays 1988). The simplified function is:

$$Log\ p = \bar{y} + K_t\ S_y \qquad (1)$$

where p, $\bar{y}$, k_t and S_y are the estimated precipitation for specific frequency value, arithmetic average of y_i , frequency factor, and standard deviation. The $\bar{y}$ can be described as:

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \qquad (2)$$

where n is number of available data and y_i is:

$$y_i = \log(P_i) \qquad (3)$$

and S_y is standard deviation. The S_y function is:

$$S_y = \left(\frac{1}{n-1}\sum_{i=1}^{n}(y_i - \bar{y})^2\right)^{\frac{1}{2}} \qquad (4)$$

To compute the frequency factor, the skewness coefficient, C_s, is required (Chow, Maidment, and Mays 1988), and it is defined as:

$$C_s = \frac{n\sum_{i=1}^{n}(y_i - \bar{y})^3}{(n-1)(n-2){S_y}^3} \quad (5)$$

The frequency factor of Log Pearson type III, can be read from a readily table by knowing the skewness coefficient and the return period.

4.1.2 Gumbel distribution

One of the most common distributions used for rainfall analysis is Gumbel's extreme value distribution (Burke and Burke 2015). The general equation for Gumbel's distribution is (Chow, Maidment, and Mays 1988):

$$p = \bar{p} + KS \quad (6)$$

where *p*, $\bar{p}$, *K*, and *S* are desired rainfall for specific frequency, arithmetic average of precipitation data, Gumbel frequency factor, and standard deviation. The $\bar{p}$ function is*:*

$$\bar{p} = \frac{1}{n}\sum_{i=1}^{n} p_i \quad (7)$$

where p_i is the individual extreme individual value of precipitation data and *n* is the number of data. The S is calculated by:

$$S = \left(\frac{1}{n-1}\sum_{i=1}^{n}(p_i - \bar{p})^2\right)^{\frac{1}{2}} \quad (8)$$

The frequency factor *k* is a given data and is a function of sample size and return period (Chow, Maidment, and Mays 1988).

4.1.3 Generalized Extreme Value distribution (GEV)

Jenkinson (1955) introduced Generalized Extreme Value (GEV) distributions for cumulative distribution models for univariate extreme values. GEV distributions combine three extreme value distributions, the Gumbel, Fréchet and reverse Weibull distributions, into one distribution. Mathematically, the GEV can be defined as:

$$F_{GEV}(X) = \begin{cases} exp\left\{-\left[1+K\left(\frac{x-\mu}{\alpha}\right)\right]^{-\frac{1}{k}}\right\}, & k \neq 0 \\ \exp\left\{-\exp\left[-\left(\frac{x-\mu}{\alpha}\right)\right]\right\}, & k = 0 \end{cases} \tag{9}$$

where μ, α and k indicate the location, scale, and shape parameter, which in practice usually lie in the range [-1/2 ,1/2] (Hosking, Wallis, and Wood 1985). The behavior of tails of the distribution is established by shape parameter; k > 0 implies a finite lower bound, $\mathrm{L} = \mu - {}^{\alpha}/_{k}$ and a heavy upper tail (Fréchet distribution), whereas for k <0 implies a finite upper limit, $\mathrm{U} = \mu - {}^{\alpha}/_{k}$ (reverse Weibull distribution). For $k=0$, the GEV distribution degrades to a Gumbel distribution (Rulfová et al. 2016). The Probability Weighted Moments (PWM) of GEV distribution for $k \neq 0$ are given:

$$\beta_r = \frac{\mu+\alpha\{1-(r+1)^{-k}\sum(1+k)/k}{r+1} \quad , \qquad k > -1 \tag{10}$$

For k ≤ -1, the mean of the distribution (β_0) and the rest of β_r do not exist (Hosking, Wallis, and Wood 1985). After calculating the PWMs, it is possible to assign a return period for each specified depth and intensity. The return period T can be defined as:

$$T = \frac{1}{[1-F(x)]} \tag{11}$$

The concept of the return period is traditionally used to design and estimate the service level of stormwater facilities system. A design based on 100-yr return period theoretically means that the facility is designed to handle stormwater generated from events that are most likely to occur about once in one 100 years. Therefore, it has a probability of 1% of occurring in any given year (Mailhot and Duchesne 2010).

4.2 Hydrological modeling

A calibrated stormwater management model was used to evaluate the infrastructure's functionality according to current and future design storms for different durations. The XPSWMM model accounts for the different hydrologic processes that affect the amount of runoff from urban areas. The hydrological process include, but is not limited to, evaporation of surface water and infiltration of rainfall in the different layer of soils (Rossman 2015).

To calculate the amount of runoff from a rainfall, XPSWMM uses different methods such as the Horton model, the Modified Horton infiltration model, the Green-Ampt model, the Modified Green-Ampt model, and the Curve Number (CN) model. Specifically, the *CN* method estimates runoff volumes by accounting for basin soil and cover type, rainfall depth and soil moisture (Burke and Burke 2015). The cumulative runoff R(t) volume can be determined by:

$$R(t) = \frac{(P(t) - 0.2\,S)^2}{P(t) + 0.8\,S} \tag{12}$$

where P(t) stand for cumulative rainfall (inches) and *S* can be calculated by:

$$S = \left(\frac{1000}{CN}\right) - 10 \tag{13}$$

CN can be determined according to the land cover and the soil type of the basin. The *CN* reflects the abstraction characteristic of the watershed, which varies from 0-100, having all rainfall absorbed by the soil (*CN* = 0) to having all of the rainfall as runoff (*CN* = 100). To compute the *CN* for real surfaces, the Soil Conservation Service (SCS) analyzed runoff volumes for different rainfalls for various types of known soils and land covers. At the end, the SCS provides three different *CN* values associated with each watershed. The difference between these provided *CNs* result from different Antecedent Soil Moisture Condition (AMC) (determined by total rainfall in last 5 days). Usually, the *CN* for ACMII is used to calculate the generated runoff. The ACMII soil may consider an average soil moisture condition in Illinois and Indiana, but it can also consider the lower and upper envelopes of *CN* associated with AMCI and AMCIII. The AMC criteria are presented in Table 2 (Gray and Burke 1983). A composite *CN* for basins with a variety of land uses and/or soil types can be estimated by taking a weighted average of all *CNs* associated with the various component areas.

Table 2 Antecedent Moisture Condition Criteria

AMC Class	Total 5-Day Antecedent Rainfall (inches)	
	Growing Season	Dormant Season
SCS AMCI	less than 1.4	less than 0.5
SCS AMCII	1.4 to 2.1	0.5 to 1.1
SCS AMCIII	over 2.1	over 1.1

To compute flow in the conveyance system (i.e., pipes or channels), XPSWMM can use a variety of methods depending on the type, shape, and size of the system. For open channels, XPSWMM uses the Manning equation to assess flow rate (Rossman 2015). The Manning equation is:

$$Q = \frac{1.49}{n} A\, R^{2/3}\, S^{1/2} \qquad (14)$$

where *n*, *A*, *R*, and *S* stand for manning roughness coefficient, cross-sectional area, hydraulic radius, and slope respectively. For pipes, either the Hazen-Williams or Darcy-Weisbach formulas can be used for fully pressurized flow. The Hazen-Williams and Darcy-Weisbach formulas are provided in equation 8 and 9 respectively:

$$\text{Hazen-Williams: } Q = 1.318\ C\ A\ R^{0.63}\ S^{0.54} \tag{15}$$

$$\text{Darcy-Weisbach: } Q = \sqrt{\frac{8g}{f}}\ AR^{\frac{1}{2}}\ S^{\frac{1}{2}} \tag{16}$$

where *C* is the Hazen-Williams C-factor, which is supplied as a cross section parameters. In the Darcy-Weisbach formula, *g* is the gravitational acceleration and *f* is the Darcy-Weisbach friction factor.

5. Results

In this section, estimated future rainfall depths for different types of rainfall duration will be presented and IDF curves based on the new analysis data will be compared with IDF curves based on Bulletin 70. Python was used for GEV distribution computation and regional frequency analysis; specifically, the following libraries were used: SciPy to fit GEV, Pandas and NumPy to analyze rainfall data, and NetCDF to extract Climate model data. Then, the hydrological model was used to simulate the runoff volume and evaluate stormwater infrastructure.

5.1 Climate Data Analysis

First, rainfall depths for the City of Elmhurst were extracted from the HRM3-GFDL dataset—a combination of available Reginal Climate model and Global Climate Driver—by using a Python code. Next, 3-, 6-, 12- and 24-hour rainfall data were computed. Subsequently, annual maximum rainfalls for each rainfall duration were selected regardless of their amount. The maximum precipitations for each year are provided in Table 3.

Table 3 Simulated Annual Maximum Rainfall for Selected Rainfall Durations

Year	3-hr Rainfall Depth (in)	6-hr Rainfall Depth (in)	12-hr Rainfall Depth (in)	24-hr Rainfall Depth (in)
2038	1.61	2.33	2.98	4.05
2039	1.38	2.45	3.63	5.07
2040	1.64	2.80	2.98	3.87
2041	1.65	2.42	2.68	3.84
2042	2.06	2.36	3.23	4.13
2043	3.62	5.28	6.49	6.56
2044	1.95	3.30	3.47	3.80
2045	2.21	3.58	5.05	5.21
2046	1.91	3.55	5.83	6.51
2047	1.63	2.86	3.89	3.97
2048	1.71	2.36	3.34	5.17
2049	1.89	2.77	3.78	4.37
2050	1.79	3.24	4.90	5.30
2051	2.12	2.36	2.87	3.98
2052	3.63	5.39	6.93	7.63
2053	3.8	5.69	6.04	6.29
2054	1.4	1.97	2.86	4.44
2055	5.12	5.83	6.81	8.14
2056	3.64	3.84	3.93	5.03
2057	2.86	4.81	5.52	6.27
2058	1.76	3.21	3.41	3.96
2059	4.59	5.77	5.81	6.40
2060	1.8	2.60	3.02	3.74
2061	1.96	2.69	4.65	4.74
2062	3.2	3.52	3.56	3.72
2063	3.32	3.91	4.50	4.54
2064	3.45	4.40	5.45	5.89
2065	5.67	8.46	9.61	9.61
2066	4.1	4.89	5.61	6.87
2067	4.89	8.46	9.43	9.49
2068	2.66	3.51	4.13	5.15
2069	2.81	3.65	4.53	7.01
2070	1.89	3.16	4.98	5.42

After sorting annual maximum rainfall depths in descending order, 3 types of common distributions for regional analysis were used to compute a 100-year return period rainfall depth for specified rainfall duration. In this research, Generalized Extreme Values Distribution, Log Pearson Type III Distribution and Gumbel's Extreme Value Distribution were used. The results are provided in Table 4.

Table 4 Estimated 100-year Rainfall Depths Using Specified Distribution

Distribution	**100-year rainfall depth (inches)**			
	3-hour	**6-hour**	**12-hour**	**24-hour**
Generalized Extreme Values(GEV)	6.04	8.55	9.54	9.61
Log Pearson Type III	7.35	8.58	9.81	10.95
Gumbel Extreme Value Distribution	6.91	9.58	10.78	11.16

From the estimated future 100-year rainfall depths, the Log Pearson Type III distribution was observed to be the most appropriate distribution for this region. The regional estimates were calculated by using estimated quantiles in Log Pearson Type III distribution.

The results were compared with Bulletin 70 and NOAA Atlas 14 for various rainfall durations and return periods. The results are provided in different tables according to rainfall durations (tables 5-8). Table 5 presents the comparison between the estimated rainfall depths, the Illinois Bulletin 70, and NOAA Atlas 14 for 3-hour rainfall.

Table 5 Estimated Rainfall Depths(in) Compared to Bulletin 70 and NOAA Atlas 14 for 3 hour Storm Duration

	Return Periods (Year)					
	2	**5**	**10**	**25**	**50**	**100**
Estimated Rainfall (LP(III))	2.49	3.49	4.30	5.42	6.35	7.35
Bulletin 70	1.94	2.43	2.86	3.53	4.14	4.85
NOAA Atlas 14	1.78	2.21	2.64	3.15	3.64	4.12

Table 6 indicates the comparison for 6-hour storm duration for different return periods.

Table 6 Estimated Rainfall Depths(in) Compared to Bulletin 70 and NOAA Atlas 14 for 6 hour Storm Duration

	Return Periods (Year)					
	2	**5**	**10**	**25**	**50**	**100**
Estimated Rainfall (LP(III))	3.59	4.92	5.80	6.81	7.75	8.58
Bulletin 70	2.28	2.85	3.35	4.13	4.85	5.68
NOAA Atlas 14	2.14	2.71	3.27	4.02	4.71	5.44

The comparison between estimated rainfall depth for 12-hour rainfall presents in table 7.

Table 7 Estimated Rainfall Depths (in) Compared to Bulletin 70 and NOAA Atlas 14 for 12 hour Storm Duration

	Return Periods (Year)					
	2	**5**	**10**	**25**	**50**	**100**
Estimated Rainfall (LP(III))	4.45	5.93	6.88	8.07	8.95	9.81
Bulletin 70	2.64	3.31	3.89	4.79	5.62	6.59
NOAA Atlas 14	2.46	3.09	3.71	4.53	5.29	6.09

Table 8 indicates the comparison between projected rainfall depths and the Illinois Bulletin 70, and NOAA Atlas 14 for 24-hour rainfall duration in different return periods.

Table 8 Estimated Rainfall Depths Compared to Bulletin 70 and NOAA Atlas 14 for 24 hour Storm Duration

	Return Periods (Year)					
	2	**5**	**10**	**25**	**50**	**100**
Estimated Rainfall (LP(III))	5.14	6.59	7.59	8.90	9.91	10.95
Bulletin 70	3.04	3.8	4.47	5.51	6.46	7.58
NOAA Atlas 14	2.89	3.69	4.37	5.36	6.22	7.17

Intensity-Duration-Frequency (IDF) curves were developed for 2-, 5-, 10-, 25-, 50- , 100- year recurrence intervals by using various durations (3-, 6-, 12-, 24-hour). Figure 2 shows the IDF curves resulting from this research.

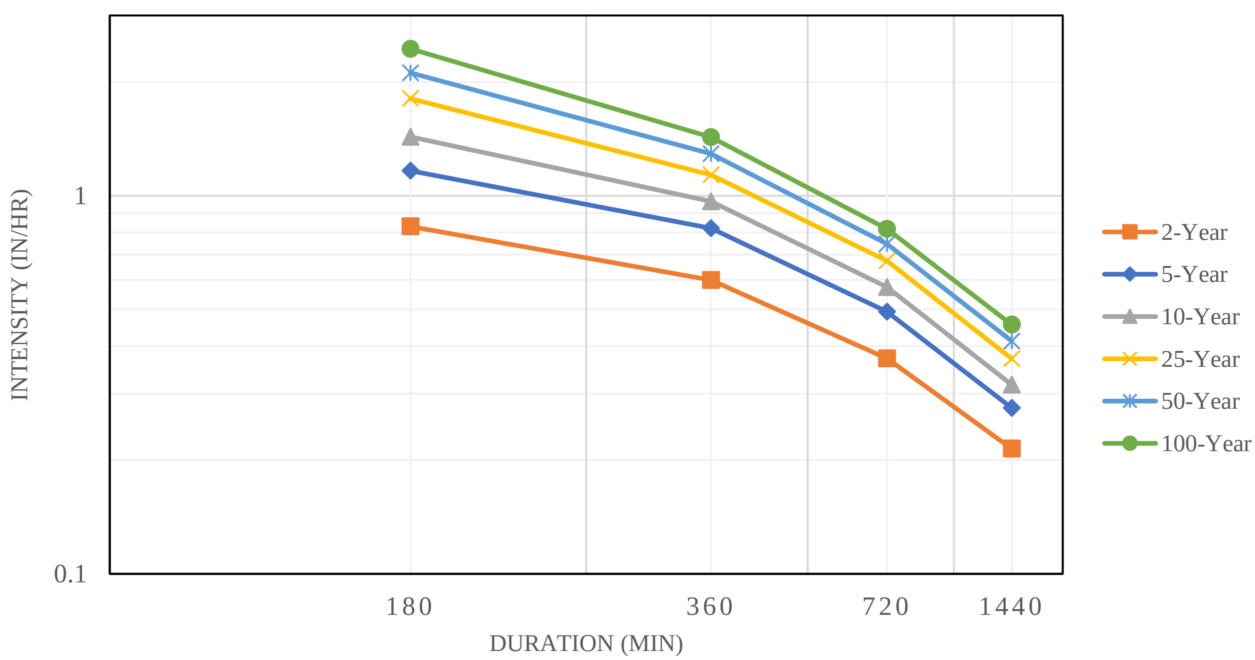

Figure 2 Intensity -Duration - Frequency Curve

The IDF curves using estimated future rainfall data and curves from the Illinois Bulletin 70 are shown in Figure 3. As can be seen, the estimated IDF curves using climate model data are higher than the Bulletin 70 curves (i.e., Bulletin 70 IDF curve for 50- and 100-year event is close to 5- and 10-year event in this research). These differences indicate the simulated effect of climate change on rainfall intensity. Data used in Bulletin 70 represents daily data for 80-year period (1901-1980) for 61 stations in Illinois, while data in this research represents climate model for 33-year period (2038-2070) for one station resulting in the discrepancy between 3-hour storm durations seen in Figure 3.

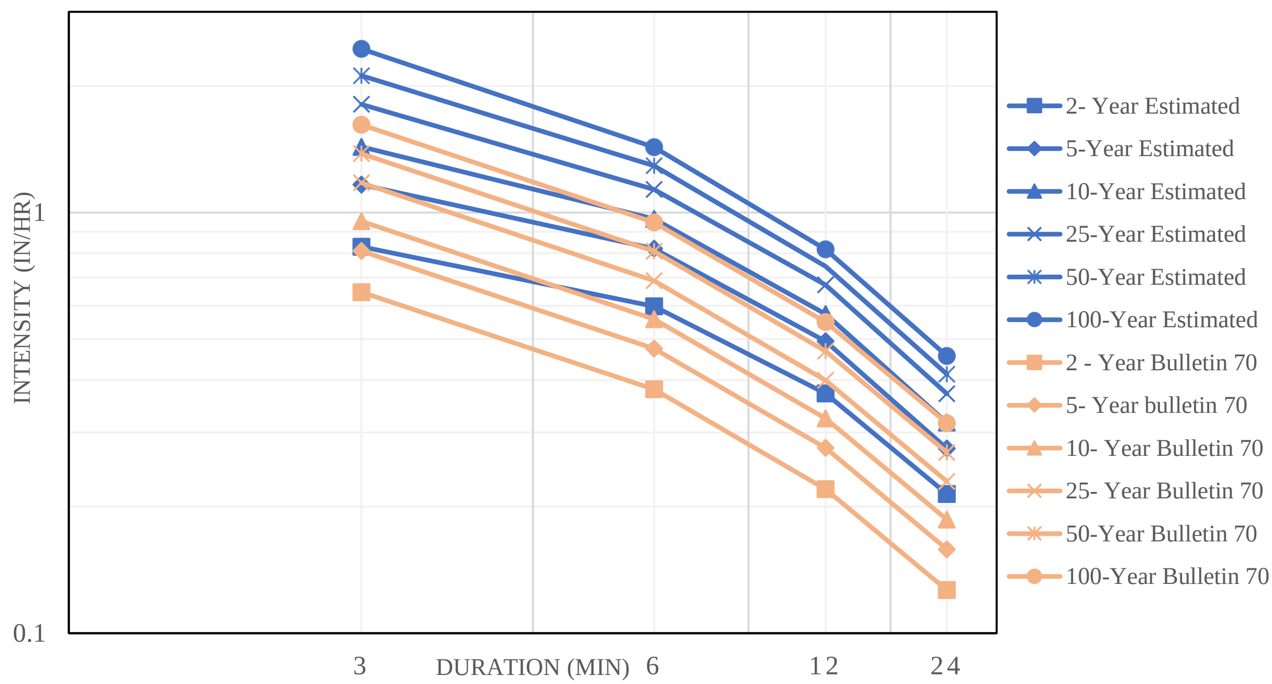

Figure 3 Comparison Between Developed IDF Curve and Bulletin 70

Differences between the Illinois Bulletin 70 and the estimated rainfall IDF curves tend to be more acute for longer durations; i.e., differences between the two sets of data are not as high for the 3-hour rainfall duration. This difference may result from the type of data used in the Illinois Bulletin 70, or from differences in longer rainfall patterns due to climate change.

5.2 Hydrological Analysis

The critical rainfall duration was used to compute the peak flowrate and runoff volume from site, which is a 2-hour rainfall duration. Since climate model data are reported for 3-hour average intensity only, a Linear Regression model was calibrated to estimate the 1- and 2-hour 100-year storm. As presented in Figure 4, the increase percentage from Bulletin 70 (table 9) was used for linear regression analysis. Then, estimated increase percentage was used to compute the 1- and 2-hour 100-year rainfall depth.

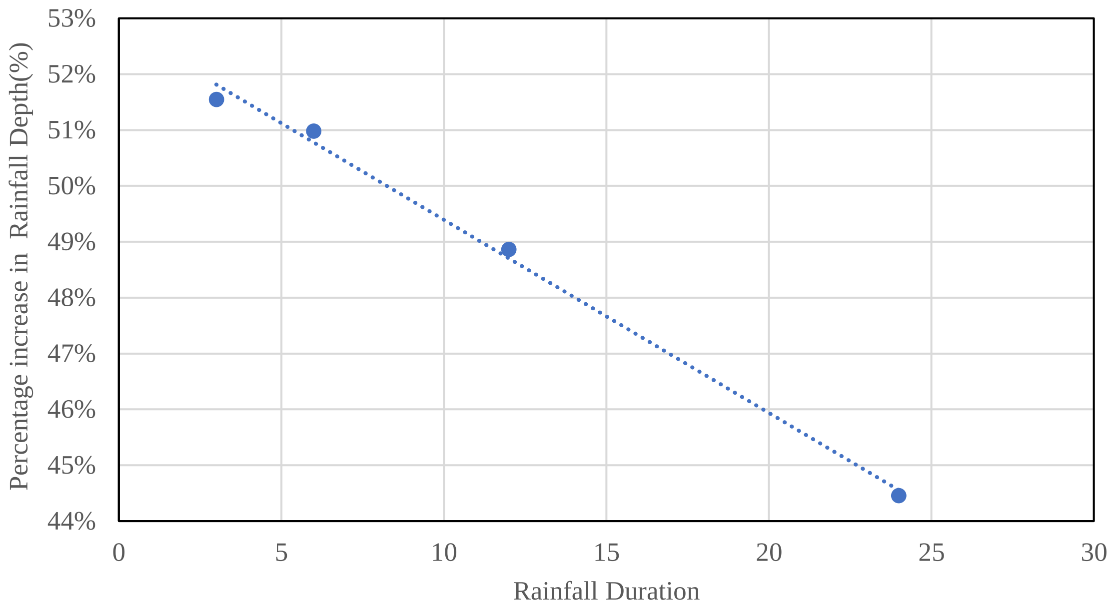

Figure 4 Regression Model to Estimate 1- and 2-hour Rainfall Depth

The estimated 100-year storm event data and the percentage increase from the Illinois Bulletin 70 for each rainfall duration is presented in Table 9. The results indicate a higher percentage of increase in rainfalls with shorter duration.

Table 9 Result of Regression Model Simulation (rainfall depth in inches)

	1-hour	**2-hour**	**3-hour**	**6-hour**	**12-hour**	**24-hour**
Estimated	5.43	6.80	7.35	8.58	9.81	10.95
Illinois Bulletin 70	3.56	4.47	4.85	5.68	6.59	7.58
Percentage Increase	52.5%	52.1%	51.5%	51.0%	48.9%	44.5%

5.3 Hydrological modeling

In this part, an overview of the hydrological modeling with XPSWMM is presented. The first part of the modeling includes simulating peak discharge and runoff volume for an existing stormwater conveyance and a proposed stormwater storage facility. The critical point for this model (lowest ground elevation, located in the Subbasin EL6) was used to evaluate the resilience of the existing and proposed stormwater management facilities to climate change. A new stormwater management facility was conceptually designed in this location to decrease the flood elevation to the street level. The designed stormwater management facility includes upsizing the storm sewer pipe in conjunction with the creation of 4 acre-feet of flood storage. A study of new stormwater management facilities provides the opportunity to evaluate the current design criteria adaptability to future design needs. The modeling area is presented in Figure 5.

Figure 5 Hydrological Modeling Study Area

The existing runoff volume and peak flow from the assigned area (presented in figure5) were simulated based on Bulletin 70 rainfall data for 1-, 2-, 3-hour 100-year rainfall as the baseline scenario. Next, runoff volume computed by assuming the soil condition and rainfall distribution (Huff Quartile one Distribution) remain the same, but the rainfall increases up to the estimated rainfall based on the climate model. The computed precipitation from climate model indicates about a 50% increase in rainfall depth from Bulletin 70. Thus, the peak flowrate and runoff volume was computed for 1-, 2-, and 3-hour 100-year future rainfall. Then the required pipe size change and storage volume were calculated (scenarios 4-6).

Due to the level of uncertainty in climate models, a 25% and 75% increase in rainfall depth from Bulletin 70 were also assumed and modeled as separate scenarios. Then, the required increase in pipe size and storage volume computed for the 25% and 75% increase in Bulletin 70's 1-, 2-, and 3-hour 100-year rainfall (scenarios 8-12).

According to a study for the Vermilion basin, IL, soil moisture will possibly diminish in the future (Tavakoli and De Smedt 2012). The NRCS (SCS) curve number method was established based on antecedent soil moisture, which indicates the average soil moisture for last 5 days before precipitation (described in section 4.2). As a result, a 35 % reduction in soil moisture is assumed to determine new *CN*s. These new *CN*s were estimated by plotting the curve numbers for ACMI, ACMII, ACMII type of soil moisture. Again, the required pipe size and storage volume determined for all 9-different rainfall (scenarios 13-21). A summary of all scenarios provided in Table10.

Table 10 Modeling Scenarios

Scenario	Description
Baseline 1	Existing soil condition for 1-hr 100yr (Bulletin 70 Rainfall data)
Baseline 2	Existing soil condition for 2-hr 100yr (Bulletin 70 Rainfall data)
Baseline 3	Existing soil condition for 3-hr 100yr (Bulletin 70 Rainfall data)
Scenario 4	Existing soil condition for estimated future 1-hr 100yr (about 50% increase in rainfall)
Scenario 5	Existing soil condition for estimated future 2-hr 100yr (about 50% increase in rainfall)
Scenario 6	Existing soil condition for estimated future 3-hr 100yr (about 50% increase in rainfall)
Scenario 7	Existing soil condition with 25% increase in 1-hr 100yr rainfall (Bulletin 70 Rainfall data)
Scenario 8	Existing Soil condition with 25% increase in 2-hr 100yr rainfall (Bulletin 70 Rainfall data)
Scenario 9	Existing soil condition with 25% increase in 3-hr 100yr rainfall (Bulletin 70 Rainfall data)
Scenario 10	Existing soil condition with 75% increase in 1-hr 100yr rainfall (Bulletin 70 Rainfall data)
Scenario 11	Existing condition with 75% increase in 2-hr 100yr rainfall (Bulletin 70 Rainfall data)
Scenario 12	Existing condition with 75% increase in 3-hr 100yr rainfall (Bulletin 70 Rainfall data)
Scenario 13	Future soil condition for estimated future 1-hr 100yr (about 50% increase in rainfall)
Scenario 14	Future soil condition for estimated future 2-hr 100yr (about 50% increase in rainfall)
Scenario 15	Future soil condition for estimated future 3-hr 100yr (about 50% increase in rainfall)
Scenario 16	Future soil condition with 25% increase in 1-hr 100yr rainfall (Bulletin 70 Rainfall data)
Scenario 17	Future soil condition with 25% increase in 2-hr 100yr rainfall (Bulletin 70 Rainfall data)
Scenario 18	Future soil condition with 25% increase in 3-hr 100yr rainfall (Bulletin 70 Rainfall data)
Scenario 19	Future soil condition with 75% increase in 1-hr 100yr rainfall (Bulletin 70 Rainfall data)
Scenario 20	Future soil condition with 75% increase in 2-hr 100yr rainfall (Bulletin 70 Rainfall data)
Scenario 21	Future soil condition with 75% increase in 3-hr 100yr rainfall (Bulletin 70 Rainfall data)

5.3.1 Conveyance System Analysis

The peak flowrate and runoff volume for the entire study area were simulated to compute the peak inflow rate for the new stormwater facility. Then, the diameter required of the pipes for each scenario were determined. The Hazen-William and Manning's equation were applied for under pressure and partially full pipe. The list of analyzed pipe names is presented in Table 11. Figure 5 indicates the location of each conduit.

Table 11 Conceptual Proposed Conduit Names

Conduit Name	Length (ft)	Diameter (in)
Link6300	660	24
Link6301	650	24
Link6302	325	24
Link6303	550	36
Link6304	433	36
4251.1	220	54
Relief	1110	54
Link6307	60	12

The estimated peak flowrate in each conduit under present conditions (Baseline 1- Baseline 3) was used as the baseline for each storm duration. Then, the peak flowrate (new design flowrate) for each scenario was computed. Next, the newly required diameter of each pipe was determined. The results are provided in tables 12- 17. The estimated storm sewer size for 1-hour rainfall duration and the existing soil moisture condition are presented in table 12. The calculation shows the conduits Link 6303, 4251.1 and Relief need to be increased between 1 to 3 nominal sizes (base on IDOT Drainage Manual).

Table 12 Calculated Pipe Diameter Based on Current Soil Moisture and 1-hour rainfall

Conduit Name	Existing Diameter (in)	Baseline 1	Scenario 4		Scenario 7		Scenario 10	
		Max flow (cfs)	Max flow (cfs)	New Diameter (in)	Max flow (cfs)	New Diameter (in)	Max flow (cfs)	New Diameter (in)
Link6300	24	16.75	16.74	24	16.94	24	16.86	24
Link6301	24	15.28	15.73	24	16.23	24	15.61	24
Link6302	24	16.34	18.91	24	17.73	24	19.77	24
Link6303	36	17.07	36.69	48	28.86	42	44.62	54
Link6304	36	30.82	33.43	36	32.37	36	34.15	24
4251.1	54	45.88	65.86	66	65.80	66	73.35	72
Relief	54	46.44	66.78	66	66.71	66	72.52	72
Link6307	12	5.39	8.34	12	6.68	12	9.50	12

Table 13 presents the estimated storm sewer pipe size based on peak discharge of different 2-hour rainfall duration for existing soil moisture condition. The results indicate the pipe size for Link 6303, 4251.1, and Relief need to be increased to avoid flooding due to an increase in precipitation depth. The storm sewer pipe diameter for each conduit should increase between 1-3 nominal sizes (0.5 -1.5 ft) regarding an increase in total rainfall depth.

Table 13 Calculated Pipe Diameter Based on Current Soil Moisture and 2-hour rainfall

Conduit Name	Existing Diameter (in)	Baseline 2	Scenario 5		Scenario 8		Scenario 11	
		Max flow (cfs)	Max flow (cfs)	New Diameter (in)	Max flow (cfs)	New Diameter (in)	Max flow (cfs)	New Diameter (in)
Link6300	24	15.31	17.02	24	16.85	24	16.87	24
Link6301	24	15.14	15.59	24	16.36	24	15.22	24
Link6302	24	15.57	18.09	24	16.90	24	18.92	24
Link6303	36	13.54	37.30	48	23.83	42	45.06	54
Link6304	36	30.47	32.68	36	32.18	36	33.45	36
4251.1	54	43.91	66.91	66	55.82	60	73.68	72
Relief	54	44.62	66.19	66	56.88	60	72.94	72
Link6307	12	6.04	9.51	12	7.79	12	10.46	12

Consequently, Table 14 represents the newly computed conduit diameter based on future projected rainfall data, in addition to the 25% and 75% increases in rainfall depths from Bulletin 70. The pipe size increases vary from 1 to 3 nominal sizes for each pipe according to the increase in rainfall depths and generated runoff volume.

Table 14 Calculated Pipe Diameter Based on Current Soil Moisture and 3-hour rainfall

Conduit Name	Existing Diameter (in)	Baseline 3	Scenario 6		Scenario 9		Scenario 12	
		Max flow (cfs)	Max flow (cfs)	New Diameter (in)	Max flow (cfs)	New Diameter (in)	Max flow (cfs)	New Diameter (in)
Link6300	24	14.22	16.75	24	16.17	24	17.00	24
Link6301	24	14.44	15.92	24	16.04	24	15.14	24
Link6302	24	14.62	17.38	24	16.12	24	18.16	24
Link6303	36	8.49	33.85	48	18.41	36	40.69	54
Link6304	36	29.03	32.82	36	31.53	36	32.84	36
4251.1	54	37.61	63.20	66	49.32	60	69.67	66
Relief	54	38.06	62.22	66	49.94	60	68.62	66
Link6307	12	6.09	9.51	12	7.63	12	10.45	12

Next, the soil moisture reduction is considered in computing the runoff volume and peak flowrate for all the discussed types of precipitation in scenario 4-12. The impact of soil moisture reduction on generated runoff volume was taken into account as the reduction in Curve Number for each subbasin. The new Curve Number for each type of land cover was computed by using linear regression model. Thus, the new composite CN was determined for each subbasin and reported based on land cover in table 15.

Table 15 New Curve Number based on 35% Reduction in Soil Moisture

Land Cover Type	CN ACMII	35% soil moisture reduction
Impervious	98	95
commercial	94	87
residential (1/4 ac)	83	71
open space (good condition)	74	69
permeable pavement	91	82

The runoff volume and peak flowrate are simulated with adjusted *CN* for each subbasin. The simulation results for adjusted *CN* indicates a small reduction in peak flowrate and runoff volume in comparison to previous scenarios (assuming the existing soil moisture condition (ACMII)). For scenario 16 (35% reduction in soil moisture and 25% rainfall increase from Bulletin 70), the maximum flowrate for all conduits simulated was less than peak flowrate for baseline 1. The results for scenario 13 and 19 indicate the need to increase the pipe size for Link 6303, 4251.1, and Relief conduit by 1-2 nominal sizes. The results for new storm sewer pipe diameter can be seen in table 16.

Table 16 Calculated Pipe Diameter Based on 35% Reduction in Current Soil Moisture and 1-hour rainfall

Conduit Name	Existing Diameter (in)	Baseline 1	Scenario 13		Scenario 16		Scenario 19	
		Max flow (cfs)	Max flow (cfs)	New Diameter (in)	Max flow (cfs)	New Diameter (in)	Max flow (cfs)	New Diameter (in)
Link6300	24	16.75	16.59	24	15.44	24	16.98	24
Link6301	24	15.28	15.82	24	14.91	24	15.52	24
Link6302	24	16.34	17.08	24	14.57	24	18.61	24
Link6303	36	17.07	25.93	42	14.57	36	37.74	48
Link6304	36	30.82	31.65	36	30.02	36	33.05	36
4251.1	54	45.88	55.62	60	43.05	54	67.264	66
Relief	54	46.44	56.74	60	43.60	54	66.86	66
Link6307	12	5.39	6.44	12	5.23	12	5.23	12

The comparison between baseline scenario for 2-hour rainfall and scenarios 14, 17 and 20 are presented in table 17. Similarly, the results for the 25% increase in rainfall based on 35% reduction in soil moisture (scenario 17) indicate a decrease in peak flowrate. The maximum calculated flowrate for Links 6303, 4251.1, and Relief indicate the storm sewer pipe diameter should increase by 1 nominal size in scenario 14, and by 2 nominal sizes for scenario 20.

Table 17 Calculated Pipe Diameter Based on 35% Reduction in Current Soil Moisture and 2-hour rainfall

Conduit Name	Existing Diameter (in)	Baseline 2	Scenario 14		Scenario 17		Scenario 20	
		Max flow (cfs)	Max flow (cfs)	New Diameter (in)	Max flow (cfs)	New Diameter (in)	Max flow (cfs)	New Diameter (in)
Link6300	24	15.31	16.59	24	14.10	24	16.64	24
Link6301	24	15.14	15.82	24	14.85	24	15.89	24
Link6302	24	15.57	17.08	24	15.12	24	17.27	24
Link6303	36	13.54	25.93	42	12.88	36	34.59	48
Link6304	36	30.47	31.65	36	29.84	36	32.69	36
4251.1	54	43.91	55.62	60	42.58	54	63.71	66
Relief	54	44.62	56.74	60	43.24	54	63.17	66
Link6307	12	6.04	6.44	12	6.02	12	9.19	12

Table 18 displays the comparison between baseline condition (for 3-hour 100-year rainfall) and maximum flowrate simulated for scenario 15, 18, and 21. One nominal pipe size increase was determined for Link 6303, 4251.1, and Relief in scenario 14. Again, no need to increase pipe size was concluded for scenario 18. Moreover, an increase by 2 nominal pipe sizes is recommend for conduits Link 6303, 4251.1, and Relief.

Table 18 Calculated Pipe Diameter Based on 35% Reduction in Current Soil Moisture and 3-hour rainfall

Conduit Name	Existing Diameter (in)	Baseline 3	Scenario 15		Scenario 18		Scenario 21	
		Max flow (cfs)	Max flow (cfs)	New Diameter (in)	Max flow (cfs)	New Diameter (in)	Max flow (cfs)	New Diameter (in)
Link6300	24	14.22	14.97	24	13.06	24	16.41	24
Link6301	24	14.44	15.86	24	14.05	24	15.94	24
Link6302	24	14.62	15.80	24	14.27	24	16.77	24
Link6303	36	8.49	18.50	36	8.55	36	31.74	48
Link6304	36	29.03	31.03	36	28.29	36	32.24	36
4251.1	54	37.61	69.67	66	36.83	54	60.93	66
Relief	54	38.06	68.62	66	37.18	54	59.94	66
Link6307	12	6.09	7.69	12	6.13	12	9.29	12

5.3.2 Storage Size Analysis

In this part, the extra required volumes for each scenario (listed in table 10) were computed. The needed volumes were determined based on the volumes of water stored in junctions EL3, EL6, and N1148, and those located in subbasin EL3, EL6, and EL4. The required storage size for the baseline scenarios is 4 acre-feet. The estimated detention sizes for existing soil condition and different rainfall scenarios are given in table 19.

Table 19 Estimated Stage Storage Table and total required storage.

Scenarios	Junction name	Water Surface Elevation (NGVD)	Street Elevation (NGVD)	Area (Acres)	stored extra water in junction (Acre-feet)	Extra storage (Acre-feet)	Total required storage (Acre-feet)
Scenario 4	EL6	674.05	672.47	1.11	1.74	4.83	8.83
	EL3	677.34	676.20	2.60	2.97		
	N1148	676.06	676.00	1.74	0.11		
Scenario 5	EL6	674.72	672.47	1.11	2.49	6.13	10.13
	EL3	677.55	676.20	2.60	3.51		
	N1148	676.08	676.00	1.74	0.13		
Scenario 6	EL6	674.31	672.47	1.11	2.03	5.97	9.97
	EL3	677.47	676.00	2.60	3.83		
	N1148	676.06	676.00	1.74	0.11		
Scenario 7	EL6	672.41	672.47	1.11	0.00	1.53	5.53
	EL3	676.79	676.20	2.60	1.53		
	N1148	675.67	676.00	1.74	0.00		
Scenario 8	EL6	671.90	672.47	1.11	0.00	1.92	5.92
	EL3	676.94	676.20	2.60	1.92		
	N1148	675.91	676.00	1.74	0.00		
Scenario 9	EL6	671.54	672.47	1.11	0.00	1.46	5.46
	EL3	676.76	676.20	2.60	1.46		
	N1148	675.72	676.00	1.74	0.00		
Scenario 10	EL6	676.58	672.47	1.11	4.55	8.45	12.45
	EL3	677.63	676.20	2.60	3.72		
	N1148	676.11	676.00	1.74	0.19		
Scenario 11	EL6	676.29	672.47	1.11	4.23	9.18	13.18
	EL3	677.87	676.20	2.60	4.35		
	N1148	676.35	676.00	1.74	0.60		
Scenario 12	EL6	676.07	672.47	1.11	3.99	8.57	12.57
	EL3	677.88	676.20	2.60	4.36		
	N1148	676.13	676.00	1.74	0.22		

According to table 19, for soil moisture ACMII, a 50% increase in rainfall depth leads to runoff volume increase of 120% - 150%, which means that the total required storage would increase by 2.2 - 2.5 times compared to the baseline runoff volume. Similarly, for the same soil moisture, the 25% increase in rainfall depth requires an increase of 38% - 50% in storage size with respect to storm duration. While the 75% increase in rainfall leads to a triple storage size required.

Table 20 Estimated Stage Storage Table and Total Required Storage by Considering 35% Soil Moisture Reduction.

Scenarios	Junction name	Water Surface Elevation (NGVD)	Street Elevation (NGVD)	Area (Acres)	stored extra water in junction (Acre-feet)	Extra storage (Acre-feet)	Total required storage (acre-feet)
Scenario 13	EL6	672.00	672.47	1.11	0.00	1.02	5.02
	EL3	676.59	676.20	2.60	1.02		
	N1148	675.49	676.00	1.74	0.00		
Scenario 14	EL6	671.72	672.47	1.11	0.00	1.71	5.71
	EL3	676.86	676.20	2.60	1.71		
	N1148	675.87	676.00	1.74	0.00		
Scenario 15	EL6	671.65	672.47	1.11	0.00	1.17	5.17
	EL3	676.65	676.20	2.60	1.17		
	N1148	675.64	676.00	1.74	0.00		
Scenario 16	EL6	670.83	672.47	1.11	0.00	0.00	4.00
	EL3	676.00	676.20	2.60	0.00		
	N1148	674.97	676.00	1.74	0.00		
Scenario 17	EL6	670.76	672.47	1.11	0.00	0.00	4.00
	EL3	676.00	676.20	2.60	0.00		
	N1148	674.95	676.00	1.74	0.00		
Scenario 18	EL6	670.35	672.47	1.11	0.00	0.00	4.00
	EL3	675.68	676.20	2.60	0.00		
	N1148	674.52	676.00	1.74	0.00		
Scenario 19	EL6	674.40	672.47	1.11	2.13	5.27	9.27
	EL3	677.36	676.20	2.60	3.02		
	N1148	676.07	676.00	1.74	0.12		
Scenario 20	EL6	674.12	672.47	1.11	1.82	5.00	9.00
	EL3	677.38	676.20	2.60	3.08		
	N1148	676.05	676.00	1.74	0.09		
Scenario 21	EL6	673.86	672.47	1.11	1.53	4.54	8.54
	EL3	677.33	676.20	2.60	2.93		
	N1148	676.04	676.00	1.74	0.08		

Table 20 represents the storage needed for future estimated rainfall while taking into account the impact of soil moisture on generated runoff volumes. The results show the water surface level for the 25% increase in rainfall depth is below the baseline level, thus there is no need to increase the size of the existing storage. While the 50% increase in rainfall depth leads to an increase in required storage size by 25%- 42%, and for the 75% increase in rainfall depth, the required storage size increase is 2.25 times higher than the baseline scenario.

5.3.3 Green Infrastructure (GI) Sensitivity Analysis

The HEC-HMS model was used to evaluate the impact of Green Infrastructure (GI) on the peak flowrate and runoff volume in urban areas. For this purpose, the study area is scaled down to subbasin CR7. The subbasin CR7 is a fully developed residential area, the *CN* for the subbasin defined as Residential (1/4 acres) – about 38% impervious (Burke and Burke 2015). The total area of subbasin CR7 is 13.11 acres, based on the definition of residential (1/4 acre lots), the total impervious area is 5.0 acres (38% of total area), which includes roads and roofs. The average roof area was assumed as 2250 square-feet, which translates to a total roof area that was estimated to be 3.25 acres, and the remaining impervious areas are assumed to be streets and driveways.

For the baseline scenario, the runoff volume and time to peak discharge are assumed by using the existing development and Bulletin 70 rainfall data for 2-, and 24-hour 100-year event. The peak discharge and runoff volume based on 2-hour 100-year rainfall are 35 cfs and 2.9 ac-ft, and for 24-hour 100-year rainfall, the peak discharge and runoff volume are 9.4 cfs and 6.1 ac-ft. In future scenarios, a 35% soil moisture reduction was assumed. Consequently, the future peak discharge and runoff volume for current development based on estimated future 2-hour 100-year rainfall data are

44.9 cfs and 3.9 ac-ft. Also, for the 24-hour 100-year rainfall the peak discharge and total runoff volume are 12.6 cfs and 7.9 ac-ft. The results of peak discharge and generated runoff volume provided in table 21.

Table 21 Computed Peak Discharge and Runoff Volume for Current Development

Rainfall Data	Rainfall Depth (in)	Peak Discharge (cfs)	Runoff Volume (ac-ft)
Bulletin 70 2-hour 100-year	4.47	35.1	2.9
Estimated 2-hour 100-year	6.8	44.9	3.9
Bulletin 70 24-hour 100-year	7.58	9.4	6.1
Estimated 24-hour 100-year	10.95	12.6	7.9

Next, a partial Green Infrastructure model was run based on current development but using permeable pavement for all impervious areas. The results indicate a small reduction in peak discharge, but the generated runoff volume remains the same. The results are presented in table 22.

Table 22 Computed Peak Discharge and Runoff Volume for Current development with Permeable Pavement

Rainfall Data	Rainfall Depth (in)	Peak Discharge (cfs)	Runoff Volume (ac-ft)
Bulletin 70 2-hour 100-year	4.47	33.6	2.9
Estimated 2-hour 100-year	6.8	44.4	3.9
Bulletin 70 24-hour 100-year	7.58	9.3	6.0
Estimated 24-hour 100-year	10.95	12.6	7.8

For sizing green roofs, the average 4 inches media depth is assumed with the void ratio equal to 0.25 (based on WMO Technical Guidance). Then, an assumption to convert 50% of roof area to green roof (0.135 acre-feet) was used in addition to all permeable pavement as fully Green

Infrastructure development. The results show a reduction in both peak discharge and runoff volume. The results are presented in table 23.

Table 23 Computed Peak Discharge and Runoff Volume for Current Development with full Green Infrastructure

Rainfall Data	Rainfall Depth (in)	Peak Discharge (cfs)	Runoff Volume (ac-ft)
Bulletin 70 2-hour 100-year	4.47	32.2	2.7
Estimated 2-hour 100-year	6.8	42.6	3.7
Bulletin 70 24-hour 100-year	7.58	9.1	5.8
Estimated 24-hour 100-year	10.95	12.4	7.7

The results indicated that the Green Roof has more impact on decreasing the peak discharge than the runoff volume, especially for short rainfall duration. Moreover, increasing the rainfall depth has a negative impact on Green Infrastructure functionality to reduce the peak discharge and runoff volume. The comparison provided in table 24.

Table 24 Comparison the Impact of GI on Peak Discharge and Runoff Volume

Scenario	Rainfall type	Rainfall Depth (in)	Peak Discharge (cfs)	Runoff Volume (ac-ft)
Baseline	Bulletin 70 2-hr 100-yr	4.47	35.1	2.9
All permeable pavement	Bulletin 70 2-hr 100-yr	4.47	33.6	2.9
Permeable pavement and 50% Green Roof	Bulletin 70 2-hr 100-yr	4.47	32.2	2.7
Current development	Estimated future 2-hr 100-yr	6.8	44.9	3.9
All permeable pavement	Estimated future 2-hr 100-yr	6.8	44.4	3.9
Permeable pavement and 50% Green Roof	Estimated future 2-hr 100-yr	6.8	42.6	3.7
Baseline	Bulletin 70 24-hr 100-yr	7.58	9.4	6.1
All permeable pavement	Bulletin 70 24-hr 100-yr	7.58	9.3	6.0
Permeable pavement and 50% Green Roof	Bulletin 70 24-hr 100-yr	7.58	9.1	5.8
Current development	Estimated future 24-hr 100-yr	10.95	12.6	7.9
All permeable pavement	Estimated future 24-hr 100-yr	10.95	12.6	7.8
Permeable pavement and 50% Green Roof	Estimated future 24-hr 100-yr	10.95	12.4	7.7

Table 24 shows the results for short and small rainfall depths. The combination of green roofs and permeable pavement leads to a significant reduction in peak discharge (5% -8.3% reduction). Results further show that using all permeable pavement in the residential area (study area land use characteristic) leads to a reduced peak discharge by 4.3% to 5.1% for rainfall depth and duration respectively. Thus, for longer storm durations, the combination of permeable pavement and green roof leads to a reduced peak discharge of 3.2% to 16% for current and future rainfalls respectively. However, no significant reduction in peak discharge is found for the scenario with only permeable pavement. Consequently, the simulated runoff volume indicates better performance to reduce runoff volume on shorter rainfall duration. To evaluate the impact on Green Infrastructure on lag time (time from start of storm runoff to time to reach the peak discharge), hydrographs were compared for different scenarios. Figure 6 shows the impact of Green Infrastructure on peak discharge and time to peak for existing condition. The hydrograph shows that Green Infrastructure leads to small reduction in peak flow and run off volume, but the time to peak remains the same.

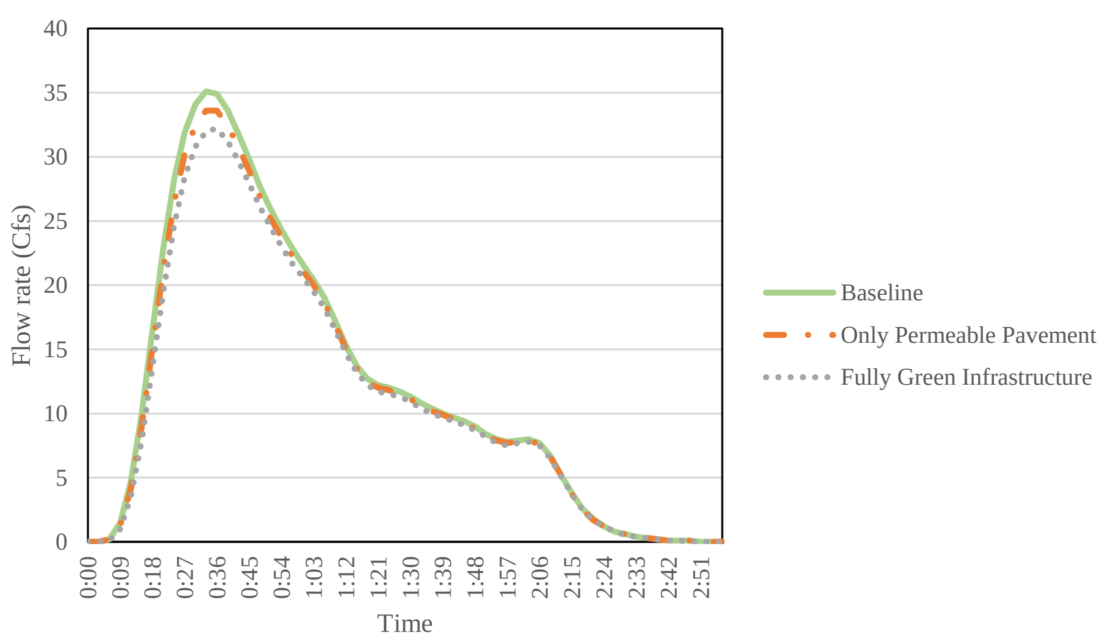

Figure 6 Comparison Hydrograph for Current 2-hour 100-year rainfall

The impact of Green Infrastructure on reducing the peak flow and runoff volume for future 2-hour 100-year rainfall is presented in Figure 7. Figure 7 shows that the hydrograph for existing development and for using only permeable pavement overlap one another, which means that with an increasing rainfall depth, the permeable pavement loses its capability to reduce the peak discharge and generated runoff volume.

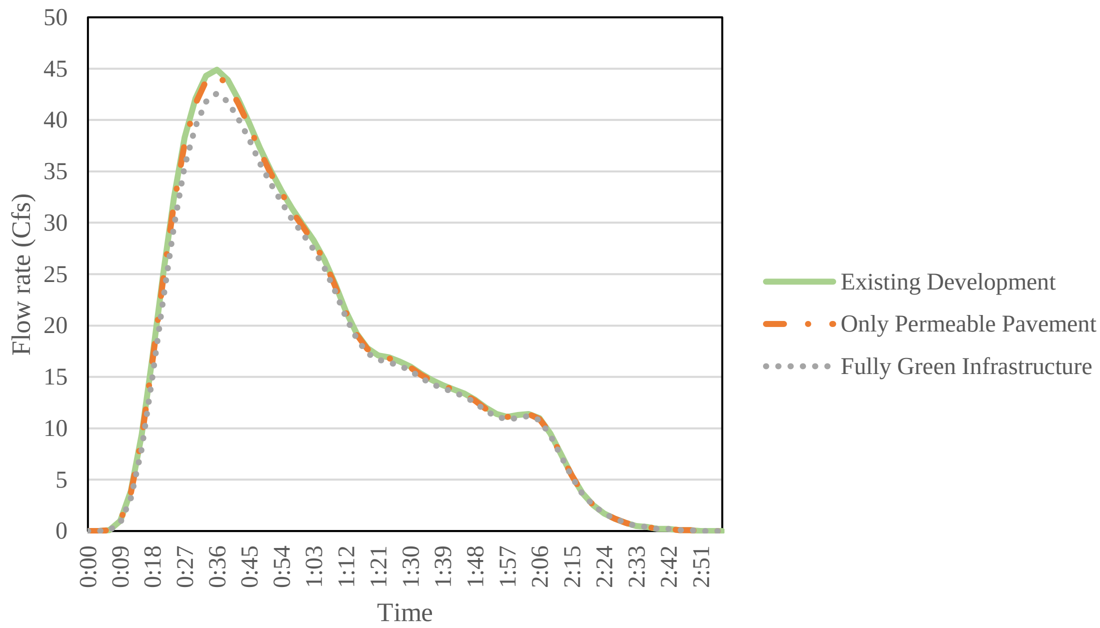

Figure 7 Impact of Green Infrastructure on Estimated Future Runoff from 2-hour 100-year

Similarly, the 24-hour 100-year rainstorm hydrograph is provided in Figure 8. The hydrograph shows that Green Infrastructure cannot reduce peak flow or runoff volume generated for 24-hour 100-year event based on Bulletin 70 rainfall data.

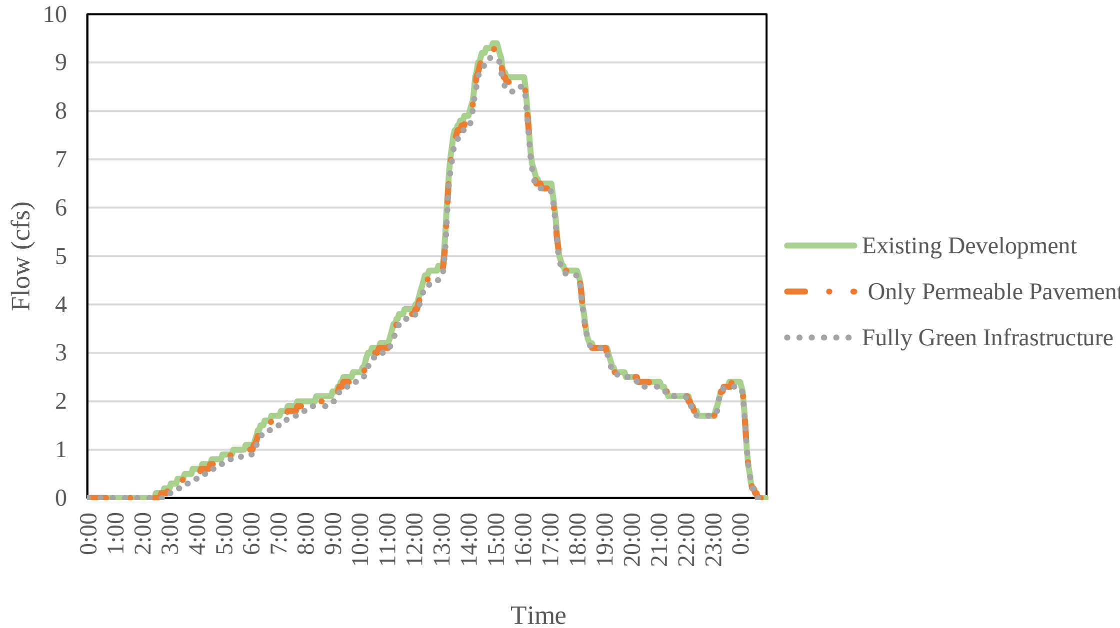

Figure 8 Comparison Hydrograph for Current 24-hour 100-year rainfall

The comparison hydrograph for the projected 24-hour 100-year rainfall is presented in figure 9. The figure shows that all 3-different hydrographs are overlapping one another. The results suggest that the permeable pavement and green roofs (overall Green Infrastructure) have better performance to overcome shorter rainfall with lower intensity.

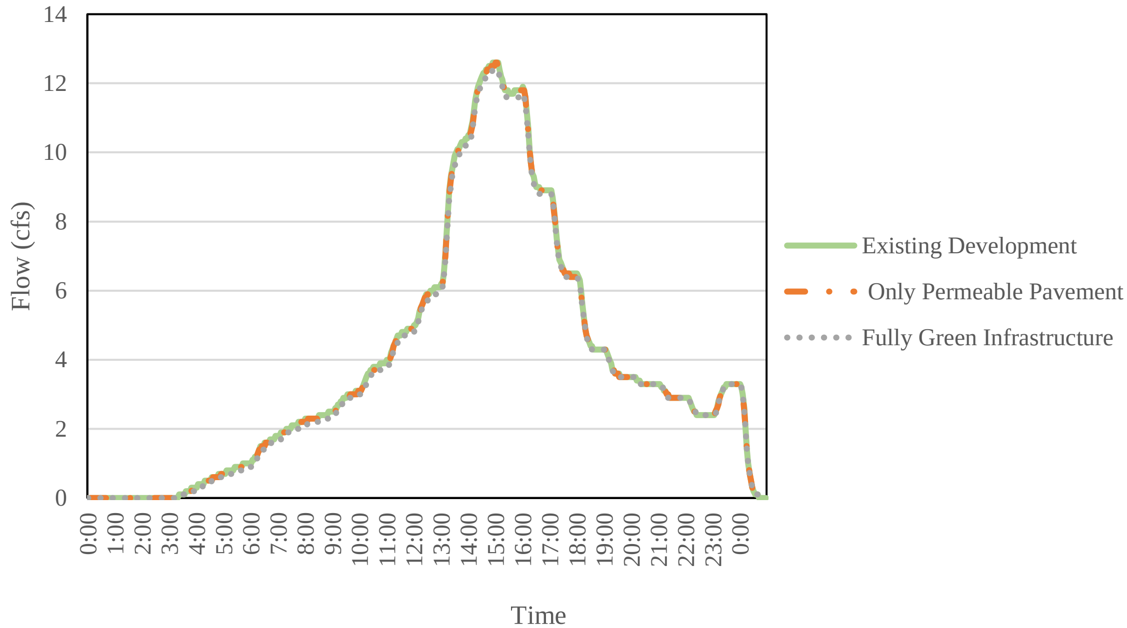

Figure 9 Impact of Green Infrastructure on Estimated Future Runoff from 24-hour 100-year

6. Conclusion

The main goal of this dissertation was to estimate the impact of climate change on existing stormwater infrastructure. To achieve this goal, future rainfall was estimated based on NARCCAP climate model dataset. The HRM3-GFDL selected from all the combination of different RCMs and GCMs (see table 1).

The annual maximum rainfall depth for 3-, 6-, 12-, and 24- hour duration within period 2038-2070 were calculated in Python. Then, the Log Pearson Type III distribution was selected as the best distribution to fit the data for all different durations. Next, the rainfall depths for six recurrence intervals (2-, 5-, 10-, 25-, 50-, 100-year) were estimated.

The estimated rainfalls from this research were compared with rainfall data obtained from NOAA Atlas 14 and Bulletin 70. The Intensity-Duration-Frequency (IDF) curves were estimated for the future rainfall data for all six recurrence intervals. The comparison IDF curve between estimated rainfall and Bulletin 70 shows IDF curves to be next to each other. The 3-hour rainfall from Bulletin 70 is slightly higher than the estimated future one.

A regression model was used to compute the critical rainfalls (1-, 2-, and 3-hour 100-year rainfall). The estimated future rainfall data shows a 52% increase from Bulletin 70 data. To account for the uncertainty in climate models, 25% and 75% increases from Bulletin 70 rainfall data was also used in hydrological modeling.

XPSWMM was used to simulate the peak flowrate and runoff volume from the study site for 21 different scenarios, included 3 baseline scenarios (using 3 different critical rainfall) for existing conditions, 9 scenarios as future estimated rainfall data, 25%, and 75% increases from Bulletin 70 rainfall data for existing conditions, and 9 scenarios for future estimated rainfall data, 25%, and 75% increase from Bulletin 70 rainfall data assuming a 35% reduction in soil moisture (see table 10).

The XPSWMM simulation results suggested 1-3 nominal storm sewer pipe size increases (according to IDOT design manual) in 3 critical conduits for 25%, 50%, and 75% increase in rainfall depth from Bulletin 70 rainfall data for existing soil moisture conditions. Furthermore, the results estimated 1-2 nominal size increases for 50%, and 75% rainfall increase from Bulletin 70 rainfall data.

The runoff simulation determined for existing soil moisture condition (ACMII), 25% increase in rainfall depth led to a 38%-50% rise in the storage volume, and 50% growth in rainfall depth led to an increase in the total required storage volume of 2.2-2.5 times higher than that of in the baseline. Moreover, the 75% increase in rainfall depth required tripling the size of the storage. However, by considering 35% reduction in soil moisture leads to a reduction in required storage for the same rainfall depths. For example, for 25% increase in rainfall depth, there is no need to increase the storage volume, and for 50% and 75% increase the total storage volume will need to rise by 25%-42%, and 2.25 times the current total volume (which is like 25% and 50% increase in rainfall depth for AMCII soil moisture).

The HEC-HMS model was used to evaluate the Green Infrastructure sensitivity analysis. In this part, 2- and 24-hour 100-year estimated rainfall data and obtained data from Bulletin 70 was used for existing development, using all permeable pavement, and assuming 50% green roofs in addition to permeable pavement. The results indicated a no significance in reduction in peak flowrate and generated runoff volume for 2-hour rainfall, but it did not have a noticeable impact on 24-hour rainfall.

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APPENDICES

Appendix A: Retrieving Climate Data from Climate Models

This is a Python code for retrieving the rainfall data from climate model to estimate the future design storm.

Few important notes:

1. Data was downloaded from NARCAAP (https://www.earthsystemgrid.org/project/narccap.html)
2. Python code was used to retrieve the data. The code is:

```
import netCDF4
import pandas as pd
from datetime import date
import datetime as dt
import numpy as np


#Creating function with the necessary arguments for analysis:
  ""it's analyzed netCDF file on selected point and create CSV file
     Args:
     path: file location
    xc= count of latitude
     yc= count of longitude""

# Reading netCDF4 file
nc = netCDF4.Dataset(path, mode='r')
df_data= pd.DataFrame(nc.variables)
df_data['Precipitation']=pd.DataFrame(nc.variables['pr'][:,yc,xc])
df_data['Time']=pd.DataFrame(nc.variables['time'][:])

df_data['Time']=[]
 for i in range(len(df_data.index)):
   start = date (1968, 1, 1)
   days = df_data['Time'][:]
   delta_time = dt.timedelta ([days[]])
   offset =delta_time +start
    df_data.append([offset])

df_data.to_csv('HRM3_GFDL2066.csv',index=False)
```

```
#Extracting different type of rainfall duration
data = pd.read_csv (path)
result = []

#24-hour rainfall
for i in range (len (data.index)):
    result.append ([ data['Time'][i], data['depth'][i:i + 8].sum()])


 data_new24 = pd.DataFrame(result)
 data_new24.columns = ['Time', 'sum']

#12-hour rainfall
for i in range (len (data.index)):
    result.append ([ data['Time'][i], data['depth'][i:i + 4].sum()])


 data_new12 = pd.DataFrame(result)
 data_new12.columns = ['Time', 'sum']

#6-hour rainfall
for i in range (len (data.index)):
    result.append ([ data['Time'][i], data['depth'][i:i + 2].sum()])


 data_new6 = pd.DataFrame(result)
 data_new6.columns = ['Time', 'sum']


# find annual max for 12-hour rainfall

max_rain = []

for i in range (0, len (data_new12.index), 2920):
    max_rain.append ([data_new12['Time'][i], max (data_new12['depth'][i:i + 2920])])

    max_rainfall = pd.DataFrame (max_rain)
    max_rainfall.columns = ['time', 'max_sum']
    max_rainfall.to_csv ('HRM3_GFDL_annualmax12.csv', index=False)
```

```python
# find annual max for 6-hour rainfall

max_rain = []

for i in range (0, len (data_new6.index), 2920):
    max_rain.append ([data_new6['Time'][i], max (data_new6['depth'][i:i + 2920])])

    max_rainfall = pd.DataFrame (max_rain)
    max_rainfall.columns = ['time', 'max_sum']
    max_rainfall.to_csv ('HRM3_GFDL_annualmax6.csv', index=False)
```

Appendix B: Curve Number for Hydrological Modeling

Table 25 Curve Number for Existing Soil Condition

Subbasin ID	Area (acres)	Curve Number
CR1	7.7	94
CR2	23.3	85
CR3	7.36	85
CR4	5.95	92
CR5	6.58	83
CR6	1.18	83
CR7	13.11	83
CR8	0.84	83
CR9	9.47	82
CR10	4.02	83
CR11	8.58	80
CR12	9.35	83
CR13	10.22	83
CR14	3.47	83
CR15	2.16	83
CR16	1.34	83
EL1	11.34	83
EL2	3.64	83
EL3	6.48	83
EL4	8.58	83
EL5	6.55	84
EL6	3.7	83
EL7	22.35	78
EL8	28.11	76
EL9	41.69	76

Table 26 Curve Number for Future Soil Condition (35% Reduction in Soil Moisture)

Subbasin ID	Area (acres)	Curve Number
CR1	7.7	87
CR2	23.3	79
CR3	7.36	74
CR4	5.95	84
CR5	6.58	71
CR6	1.18	71
CR7	13.11	71
CR8	0.84	71
CR9	9.47	73
CR10	4.02	71
CR11	8.58	71
CR12	9.35	75
CR13	10.22	71
CR14	3.47	71
CR15	2.16	71
CR16	1.34	71
EL1	11.34	74
EL2	3.64	72
EL3	6.48	71
EL4	8.58	71
EL5	6.55	73
EL6	3.7	71
EL7	22.35	72
EL8	28.11	71
EL9	41.69	71

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