Storm Sewer Infrastructure Planning with Climate Change Risk: The City of Alexandria Virginia Case Study

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Abstract: The City of Alexandria, Virginia, has experienced repeated and increasingly frequent flooding events attributable to old infrastructure, inconsistent design criteria, and perhaps climate change. The purpose of this project is to provide a program that, over a period of up to 5 years, will analyze storm sewer capacity issues, identify problem areas, develop and prioritize solutions, and provide support for public outreach and education. The purpose of the first task was to review and propose revisions to the City’s stormwater design criteria, including benchmarking of design criteria from neighboring jurisdictions, updated precipitation frequency results, evaluation of climate change risk. This paper summarizes potential changes in intensity, duration, and frequency (IDF) values, as well as sea level rise values, that were determined based on the results of general climate models paired with a range (low to high) in greenhouse gas emission scenarios. In addition, modeling of stormwater capacity under current design storm and projected storm intensity for the year 2100 are presented.

Keywords: Climate Change, Precipitation Intensity-Duration-Frequency, Sea Level Rise, Climate Change Risk Assessment

INTRODUCTION

The City of Alexandria, Virginia, (City) has experienced repeated and increasingly frequent flooding events attributable to old infrastructure, inconsistent design criteria, and perhaps climate change. The purpose of this project is to provide a program that, over a period of up to 5 years, will analyze storm sewer capacity issues, identify problem areas, develop and prioritize solutions, and provide support for public outreach and education.

The purpose of the first task is to review and propose revisions to the City’s stormwater design criteria, including potential changes in precipitation intensity, duration, and frequency (IDF) values based on the results of general climate models paired with a range (low to high) in greenhouse gas emission scenarios. IDF curves used by the City were updated based on longer historical climate data. The updated IDF curves were based on statistical analysis of additional historical climate data and compared to the IDF curves derived from climate change scenarios. To evaluate climate change adaptation options and the risk associated with different mitigation strategies, the IDF curves are used as input for new hydrologic and hydraulic models of the City’s storm sewer infrastructure. These models will be used to evaluate cost and risk associated with different mitigation scenarios and different assumptions for rain design storms and sea level rise in 2050 and 2100. The analysis was first conducted on a pilot watershed, from which the revised design criteria for storm IDF curves and sea level rise hydraulic boundary conditions will be recommended and applied to develop a citywide storm sewer master plan.

METHODS

Results from five general circulation models using low, medium, and high greenhouse gas emission scenarios were used to generate projected changes in monthly and annual precipitation for the years 2050 and 2100. The projected changes were applied to the historical daily precipitation record for
the period 1948 to 2008 to produce updated IDF values for durations ranging from 5 minutes to 96 hours for return intervals ranging from 2 to 500 years.

The SimCLIM modeling tool (Warrick, 2005), developed by CLIMsystems Ltd. in New Zealand, provides an environment in which the impacts of climate on the environment can be examined. SimCLIM merges historical climate information with global climate change projections to provide users with the ability to conduct sensitivity analysis and examine sector impacts of climate change. SimCLIM stores General Circulation Model (GCM) results and Intergovernmental Panel on Climate Change (IPCC) greenhouse gas emissions scenarios based on the Special Report Emissions Scenarios (SRES) allowing a variety of options to determine the range of results from a specific GCM using a variety of available emission scenarios. SimCLIM produced monthly precipitation projections from 1990 to 2100 from low, medium, and high emissions scenarios. Monthly precipitation projections are aggregated to annual totals, as shown on Figure 1.

FIGURE 1
Projected Changes in Annual Precipitation for Ronald Reagan Washington National Airport Using the Median of Five GCMs and Three SRES Emission Scenarios for the Years 1990 to 2100. [10 inches = 25.4 centimeters]

GCM results are produced at a coarse resolution, approximately 100 to 200 kilometers, and must be downscaled to capture the effects of local climate characteristics. Statistical downscaling is a two-step process basically consisting of 1) development of statistical relationships between local climate variables (e.g., surface air temperature and precipitation) and large-scale predictors, and 2) application of such relationships to the output of GCM to simulate local climate characteristics. The SimCLIM application uses statistical downscaling to create 1 kilometer monthly projected “climate surfaces” using historical monthly average interpolated climate elements. The method is fully described by Santer et al. (1990) and replicates local climate characteristics in Alexandria, Virginia. The historical monthly average climate elements used for the downscaling are further described in Hijmans et al. (2005).
EXTREME VALUE ANALYSIS APPROACH
Past climate data can be queried through a SimCLIM extreme event analysis tool which can
determine the probability of a particular extreme event, such as heavy rainfall. The probabilities and
return periods for such extreme events are queried for the future by using the selected GCM and
greenhouse gas emission scenarios.

SimCLIM uses the generalized extreme value (GEV) statistical analysis to model extremes of
natural phenomenon (Fisher, and Tippett, 1928). The differences between the monthly projected
precipitation values and the average monthly precipitation from the historical base period (1948 to
2008) are determined, and the percent difference is prorated and applied to the daily values for the
period selected (1948 to 2008). The resulting daily time series is adjusted by the projected GCM
results and analyzed by the GEV statistical process.

GENERAL CIRCULATION MODEL AND EMISSION SCENARIO PROCESSING
SimCLIM calculated precipitation values for durations ranging from 1 hour to 4 days and return
periods from 2 to 500 years. Results from the Ronald Reagan Washington National Airport hourly
data were scaled to 5-, 10-, 15-, and 30-minute durations using the N-minute ratios developed
separately in a statistical analysis of historical rainfall data. Projected values for 1-, 2-, 3-, 6-, and
12-hour durations were scaled by the ratios of the corresponding durations from 1948 through 2008
using the projected 24-hour precipitation value as the base. Applying the historical ratios to the
projected 24-hour precipitation value resulted in a smooth transition for precipitation values for
durations ranging from 5 minutes to 24 hours.

The years 2050 and 2100 were used as target dates for all SimCLIM model runs. A total of 2,310
values were produced from the GCMs and emissions scenarios for the durations, return periods, and
target years shown in Table 1.

Table 1: GCMs, Emission Scenarios, Durations, Return Periods, and Target Years Used to Assess Projected Climate Change Impacts on Alexandria IDF Curves

<table>
<thead>
<tr>
<th>General Circulation Models Used in Alexandria, VA IDF Project</th>
<th>Emission Scenarios</th>
<th>Durations</th>
<th>Return Periods</th>
<th>Target Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCCMA3.1 (Canada)</td>
<td>A1FI (high)</td>
<td>5-, 10-, 30-minute</td>
<td>2, 5, 10, 20, 50, 100, 500 years</td>
<td>2050, 2100</td>
</tr>
<tr>
<td>MRI-2.3.2 (Japan)</td>
<td>A1B (medium)</td>
<td>1-, 2-, 3-, 6-, 12-hour</td>
<td>1, 2, 4-day</td>
<td></td>
</tr>
<tr>
<td>ECHO-G (Germany/Korea)</td>
<td>B1 (low)</td>
<td>1, 2, 4-day</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GFDLCM2.0 (USA)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>HadCM3 (United Kingdom)</td>
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</tbody>
</table>

To optimize the presentation of results, the SimCLIM application was run in GCM “ensemble”
mode using the high, medium, and low emission scenarios to provide a consensus range of
precipitation values for the GEV process. The ensemble option calculates the median value (third
place in terms of the magnitude) from the five GCMs and emission scenarios used in this study.

RESULTS
Results from five general circulation models using low, medium, and high greenhouse gas emission
scenarios were used to generate projected changes in monthly and annual precipitation for the years
2050 and 2100. The projected changes were applied to the historical daily precipitation record for
the period 1948 through 2008 to produce updated IDF values for durations ranging from 5 minutes
to 96 hours for return intervals ranging from 2 to 500 years.
Figure 2 illustrates projected changes in return period (in years) for the 24-hour precipitation using observed daily precipitation (1948-2008), ensemble projections for 2050 and 2100 from 5 GCMs and 3 emissions scenarios. Using GCM results for the A1FI emissions scenario for the year 2100, the historical 24-hour 100-year precipitation value of approximately 7.7 inches (19.6 cm) would approach a 50 year event. From a different perspective, the 100-year 24-hour amount of 7.7 inches would become 8.2 inches (20.8 cm) using the A1FI emissions scenario in 2100.

**Figure 2:** Illustration of projected changes in return period (in years) for the 24-hour precipitation using observed daily precipitation (1948-2008), ensemble projections for 2100 from 5 GCMs and 3 emissions scenarios. [1 inch = 2.54 centimeters]

Figure 3 illustrates projected changes in the 10-year IDF rainfall intensities for 2100 based on ensemble results from five GCMs and three SRES emission scenarios compared with existing city of Alexandria, Virginia, IDF values and SimCLIM analysis of historical record for the years 1946 through 2008. For the 10-year return period, projected IDF values are less than existing IDF values for durations less than 12 hours and greater for durations from 24 to 96 hours indicating that existing IDF values for durations less than 12 hours were conservative and designed to accommodate greater precipitation amounts.

For the 2-year return period, projected IDF values for 2050 are less than existing Alexandria IDF values for durations from 5 minutes to 24 hours. When compared to NOAA Atlas 14, projected IDF values for durations decrease slightly for 48 and 96 hour durations. For the 10-year return period, projected 2050 IDF values are less than existing Alexandria IDF values for durations from 5 minutes to 24 hours. When compared to NOAA Atlas 14, projected IDF values for durations increase slightly for 48 and 96 hour durations. For the 100-year return period, projected IDF values for 2050 are less than the existing Alexandria IDF values for durations from 5 minutes to 12 hours and higher for the 24 hour duration. When compared to NOAA Atlas 14, projected IDF values for durations increase slightly for 48 and 96 hour durations.
For the 2-year return period, projected IDF values for 2100 are less than existing Alexandria IDF values for durations from 5 minutes to 24 hours. When compared to NOAA Atlas 14, projected IDF values for durations increase slightly for 48 and 96 hour durations. For the 10-year return period, projected 2100 IDF values are less than existing Alexandria IDF values for durations from 5 minutes to 24 hours. When compared to NOAA Atlas 14, projected IDF values for durations increase slightly for 48 and 96 hour durations. For the 100-year return period, projected IDF values for 2100 are less than the existing Alexandria IDF values for durations from 5 minutes to 12 hours and higher for the 24 hour duration. When compared to NOAA Atlas 14, projected IDF values for durations increase slightly for 48 and 96 hour durations.

Because of the potential infrastructure cost implications of changing drainage design criteria, the City of Alexandria is recommended to initially adopt the NOAA Atlas 14 or L-Moment results, which are generally lower than the City’s current IDF curves, but are based on a much more complete historical data set and statistical analysis. As part of the pilot watershed analysis of drainage facility needs, the City will be conducting a cost-benefit analysis of the costs and risks associated with the lower NOAA Atlas 14 curves compared with the higher projected 2100 IDF curves (and the sea level rise impacts on downstream hydraulic constraints). When costs are weighed against the risks of either reducing the IDF curves (as would be the recommendation by using NOAA Atlas 14) or increasing the IDF curves (as would be the recommendation based on projected 2100 rainfall intensities) will provide a better understanding of the implications of changing the City’s design criteria.

SEA LEVEL RISE
SimCLIM results using five general circulation models using low, medium, and high greenhouse gas emission scenarios were used to generate projected changes in mean sea level and mean higher
high water (MHHW) at the Washington D.C. gauge near the City of Alexandria for the years 2050 and 2100.

As shown in Figure 4, the projected median sea level rise from the five GCMs and three greenhouse gas scenarios ranges from 1.76 to 2.44 feet North American Vertical Datum (NAVD) (53.6 to 74.4 cm) by the year 2100. The 10 and 90 percent non-exceedence ranges are 1.33 and 3.35 feet NAVD (40.5 to 102.1 cm), respectively.

The projected median MHHW sea level rise from the five GCMs and three greenhouse gas scenarios ranges from 3.35 to 4.05 feet (NAVD) (102.1 to 123.4 cm) by the year 2100. The 10 and 90 percent non-exceedence ranges are 2.94 and 4.96 feet (NAVD) (89.6 to 151.2 cm) respectively.

A review of relevant literature on sea level rise in the Chesapeake Bay area was conducted. The literature indicated a range of sea level rise from 2.7 to 3.4 feet in one study, and from 1.6 to 4.6 feet in another study by 2100. The literature generally corroborates the projections developed in this study.

Therefore, it is projected that future infrastructure planning take into account possible increases in sea level of between 3.3 and 4.0 feet for MHHW (101 to 122 cm), in addition to water levels projected in the Potomac River, because of storm surge and flood flows in the Potomac River. With current 10-year water surface elevations in the Potomac River of approximately 5.4 feet NAVD (1.64 m), the projected water surface for the 10-year event with sea level rise is between 8.7 and 9.4 feet NAVD (2.65 to 2.86 m). Similarly, with current 100-year water surface elevations in the Potomac River of approximately 9.9 feet NAVD, the projected water surface for the 100-year event with sea level rise is between 12.2 and 13.9 feet NAVD (3.71 to 4.24 m).

CONCLUSION

A method has been demonstrated to integrate historical precipitation intensity, duration, and frequency analysis with GCM projections to assess potential changes in precipitation amounts and associated return periods to facilitate storm sewer planning and design. A companion method has
been demonstrated to estimate projected sea level rise in coastal areas using GCM sea level projections. These methods provide water managers with a tool to assess the potential impacts of more intense and frequent precipitation events and sea level rise for specific areas worldwide.

The method applied the SimCLIM software application to quickly derive changes in expected rainfall intensity-duration-frequency for the City of Alexandria, Virginia, based on the ensemble average of 5 GCMs with 3 greenhouse gas emission scenarios, to bracket the range of projected IDF values in 2050 and 2100. Similarly, these same GCM and emission scenario combinations were used to summarize projected sea level rise. These IDF and SLR values are currently being applied in hydrologic and hydraulic models to evaluate possible climate change adaptation strategies for the City’s storm drainage infrastructure.

REFERENCES


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