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Management of an Urban Stormwater System Using Projected Future Scenarios of Climate Models: A Watershed-Based Modeling Approach

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ABSTRACT

Anticipating a proper management needs for urban stormwater due to climate change is becoming a critical concern to water resources managers. In an effort to identify best management practices and understand the probable future climate scenarios, this study used high-resolution climate model data in conjunction with advanced statistical methods and computer simulation. Climate model data from the North American Regional Climate Change Assessment Program (NARCCAP) were used to calculate the design storm depths for the Gowan Watershed of Las Vegas Valley, Nevada. The Storm Water Management Model (SWMM), developed by the Environmental Protection Agency (EPA), was used for hydrological modeling. Two low-impact development techniques – Permeable Pavement and Green Roof – were implemented in the EPA SWMM hydrological modeling to attenuate excess surface runoff that was induced by climate change. The method adopted in this study was effective in mitigating the challenges in managing changes in urban stormwater amounts due to climate change.

Keywords
Stormwater, EPA SWMM, Urbanization, Climate Change, L moment, LID

1. Introduction

During the last decade, the world has experienced many weather events that have been exceptionally extreme with widespread negative effects on ecosystems and people (Coumou and Rahmstorf, 2012). These recorded extremes are thought to be connected to an ongoing warming trend. Since the mid-20th century, the changes in the climate primarily have been associated with enhanced greenhouse gases that were induced anthropogenically (Pathak et al., 2016). These recently witnessed changes in the climate, driven by anthropogenic activity, have a close link with the alteration of the global hydrological cycle (Watt et al., 2015; Thakali et al. 2016), and are expected to intensify the normal hydrological cycle, resulting in magnified and convective rainfalls (Huntington, 2006). Changes in precipitation patterns, intensity, and magnitude of these rainfalls are leading to an increased risk of flooding, even in well-managed drainage systems.

A report of the Intergovernmental Panel on Climate Change (IPCC) states that there is a theoretical certainty that the increase in global temperature will increase global precipitation (IPCC, 2013). According to an IPCC study reported by Solomon et al. (2007), in the late 20th century, global warming resulted in a world-

wide increase in extreme rainfalls. Furthermore, climate models indicate that there is a 90% likelihood that the same trend will continue during the 21st century, in the enhanced greenhouse world (Solomon et al., 2007). A trend analysis of observed extreme rainfall events across the contiguous United States showed a rapidly increasing trend that was consistent with the projected effects of climate change (Madsen and Figor, 2007).

The population of the world has grown rapidly over the last 150 years, resulting in adverse effects on natural hydrologic characteristics at the local as well as the global scale. The changes in land use and land cover also have changed normal hydrologic behavior by altering the surface infiltration characteristics. The change in the land use is closely associated with urbanization, which increases the amount of impervious surfaces, such as parking lots and building rooftops by altering the current land use. The expected consequences of urbanization include the reduction in infiltration, lag times, and baseflow as well as an increase in peak discharge, magnitude, and frequency of surface runoffs. Rapid urbanization is making cities more vulnerable to flooding and its consequences. These challenges intensify even further in the context of climate change.

Stormwater systems for an urban area usually are designed based on one level of urbanization, implementing the results of statistical analyses from previously observed data. The fluctuating nature of climate and growing urbanization may result in the capacity being surpassed of stormwater facilities that were designed and constructed based on these conventional assumptions. The conventional approach of stormwater design assumes that the rainfall pattern is stationary, and does not incorporate the effects of future climate change (Forsee et al., 2011, Thakali et al., 2017). To be sustainable throughout in the uncertain future climate communities may choose 'no-regrets' strategies that are ideally adapted for actions common to all or most scenarios (Means et al., 2010).

The design of a stormwater infrastructure for erosion and sediment control as well as for mitigation of flooding depends on the characteristics of extreme precipitation. Essentially, a drainage design needs to consider any information regarding potential climates in the future. This information can be drawn from data of climate models, which project the future climates by taking into account those factors that force climate. The North American Regional Climate Change Assessment Program (NARCCAP) is developing a high-quality climate model data for the past and future climate scenar-ios. These climate models have sub-daily precipitation data that could be used to calculate design storm depths.

The climate model data are available in gridded form, and cannot be used directly in hydrological analyses that require climate information on local scale. However, converting gridded climate model data to a point scale is not a straightforward task. Various statistical and dynamical downscaling methods are available to assess the effects of climate change when using climate model data; however, the downscaled results are highly uncertain depending on the downscaling methods and models used. This uncertainty becomes more challenging for extreme climate events, such as extreme rainfall, since the properties of these extremes do not represent that of average events. As an alternative to complex and uncertain downscaling methods, delta change method can be used to convert climate model information to a point scale. This technique has been used previously in some studies to analyze the effects of climate change, using precipitation data from climate models (e.g., Andreasson et al., 2004; Olsson et al., 2009).

Currently, the use of hydrological and hydraulic modeling is prevalent in the management of stormwater structures. Among the modeling tools available, the Storm Water Management Model (SWMM), developed by the United States Environmental Protection Agency (EPA), is a hydrological/hydraulic model that is applicable specifically for urbanized areas. The current version of SWMM has a capability of simulating the performance of Low Impact Development (LID) controls (Rossman, 2015). LID, which is an alternative method of stormwater management, controls the runoff at the source and reduces the negative effects of urbanization. LID techniques include distributed runoff control measures, for example, permeable pavements, rain gardens, green roofs, vegetated swales, and bioretention systems (Ghimire et al., 2016). These LID practices are very effective at preserving the natural hydrological conditions of a region. In general, LID practices reduce the peak runoff by controlling runoff at the source, maintaining the natural hydrological condition of the site, and reducing the water quality problems induced by urbanization. The benefits and adoption of LID techniques have been well documented in a number of studies (e.g., Berndtsson, 2010; Deitz, 2007).

This paper summarizes research that simulated design runoff by using a watershed-based analysis in EPA-SWMM using future climate information. The objectives of this study were twofold:

1. To assess the change in design storm due to climate change by using a robust statistical approach.

2. To assess and implement flood-management measures in areas in the watershed that are prone to flooding.

The results obtained may be of use in long-term water-resource management and planning as well as in the implementation of mitigation strategies for natural disasters related to flooding that may be due to a changing climate.

2.0 Study Area and Data

Las Vegas Valley (LVV), known locally as the Valley, is located in the dry and arid climate of Clark County, Nevada, in the southwestern United States. This valley faces significant water-management issues due to the complexity of its climate. The Las Vegas region extends over a 411,000-ha catchment area, which spreads approximately 65 km from Lake Mead in the southeast to the Spring Mountains in the west. Currently, LVV is experiencing rapid population growth, and considered one of the fastest growing counties in the U.S. With rapid population growth, the land use of the area has been changing substantially, resulting in increased impervious areas.

The Valley is one of the driest and hottest parts of the U.S., and receives less than 130 mm of average annual rainfall. Climate projections indicate a decrease in total precipitation in the summer and an increase in total precipitation during the winter in this part of the United States; however, an increase in the frequency and magnitude of severe rainfall phenomena has not been ruled out (Christensen et al. 2007). In the recent decades, the LVV has experienced severe flooding every year. A statistical analysis has shown an increase in the reoccurrence of extreme precipitation events over the southwestern United States (Madsen and Figor, 2007).

The Clark County Regional Flood Control District (CCRFCD) manages the stormwater systems of the Valley, using a comprehensive master plan that is updated every five years. The latest master plan update (MPU) was released in 2013. CCRFCD has divided the Valley into 11 watersheds for the proper management of the region (CCRFCD, 2013). Located in the northwestern area of the Valley, the Gowan watershed (Figure 1) was chosen as the study area for this research. This watershed covers an area of 21630 ha, and its primary drainage facilities are detention basins connected by conveyance facilities (CCRFCD, 2008).

Gowan watershed is a major tributary to the Western Tributary of the Las Vegas Wash; most of it lies within the jurisdiction of the City of Las Vegas, and is considered the most urbanized watershed with in the Valley.

This study used two types of climate-model data to project future depths for design storms. NARCCAP data were used to predict future design depths and data from the North American Regional Reanalysis (NARR) was used to evaluate the performance of the NARCCAP projections.

2.1 NARCCAP

NARCCAP data were used for the projection of future design storm depths. The NARRCCAP datasets, which are driven by four Global Climate Models (GCMs) and projected by six Regional Climate Models (RCMs), were developed to provide the probable future climate scenarios in the of United States, Canada, and Northern Mexico (Mearns et al., 2007). Table 1 provides the list of NARCCAP data used for this study.

The aim of the NARCCAP project was to provide high-resolution climate-model data for future scenarios of research on the effects of climate change. NARCCAP data are available in 3-hourly temporal resolutions and 50-km spatial resolutions. The four GCMs provided the boundary conditions to six RCMs for an historic period of 30 years of historic period (1971-2000) and a future period of 30 years (2041-2070), using the A2 Emissions Scenario from the Special Report on Emissions Scenarios (SRES) developed according to specifications from the Intergovernmental Panel on Climate Change (IPCC) (Mearns et al., 2015).

Since its establishment, NARCCAP continuously generates climate model data from various combinations of GCMs and RCMs. As of July 2016, 12 sets of NARCCAP historic and future climate data were developed, derived from combinations of GCMs and RCMS; a two-time slice from the Community Atmosphere Model, Version 3 of the National Center for Atmospheric Research (NCAR GCM, CAM3), and the atmospheric model (AM2.1) of the Geophysical Fluid Dynamics Laboratory (GFDL).

2.2 NARR

Precipitation data generated by the NARR climate model were used to assess the performance of the NARCCAP data. The NARR datasets – which are long-term, dynamically consistent, and high-resolu-
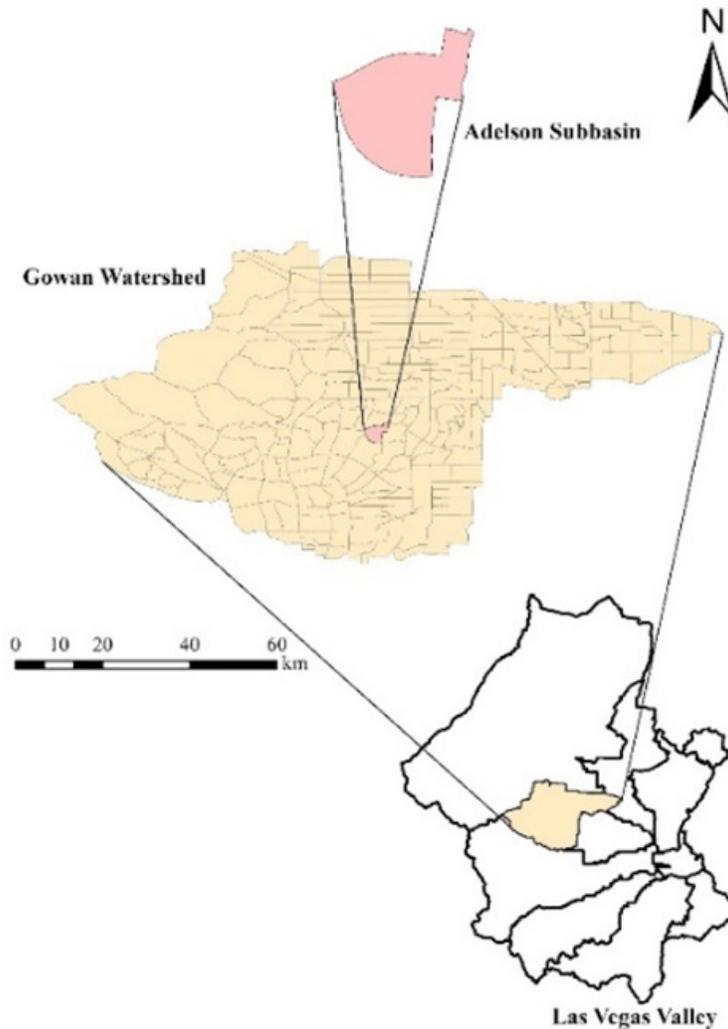
Figure 1. The Gowan Watershed within the Las Vegas Valley in southern Nevada.

tion datasets – are available for a period from 1979 to the present (Mesinger et al., 2006). The domain for the NARR data centers over North America. The NARR project is an improvement on earlier global reanalyses, having an advanced land surface model and having assimilated data for observed rainfall. Thus, NARR has successfully integrated a more accurate portrait of the land hydrology and land–atmosphere interaction, with improved atmospheric circulation throughout the troposphere (Mesinger et al., 2006). The NAAR precipitation data are available in a 3-hourly temporal resolution and a 32-km spatial resolution. The NARCCAP past data are available until 2000 thus the NARR data for the period of 1979 to 2000 were used in the analysis.

3.0 Methods

The method adopted for this study, which enabled the projection of future design storms, was categorized into a two-step procedure. First, a probability frequency was performed on the NARCCAP historic and future data as well as and NARR historic data. Second, information regarding the future design storms were used to transform the rainfall into runoff, using a hydrological modeling tool of the EPA, the Storm Water Management Model (SWMM). The transform process consisted of adjustment factors that represent future climate scenarios.

Model Combinations (GCM/RCM)	Driving Model (GCM)	RCM
CGCM3/CRCM	Third Generation Coupled Global Climate Model	Canadian Regional Climate Model
CGCM3/ RCM3	Third Generation Coupled Global Climate Model	Regional Climate Model version 3
CGCM3/WRFG	Third Generation Coupled Global Climate Model	Weather Research and Forecasting Model
CCSM/CRCM	Community Climate System Model	Canadian Regional Climate Model
CCSM/WRFG	Community Climate System Model	Weather Research and Forecasting Model
CCSM/MM5I	Community Climate System Model	MM5, the PSU/NCAR** Mesoscale Model
HaDCM3/ HRM3	Hadley Centre Coupled Global Climate Model	Hadley Regional model 3
HaDCM3/ MM5I	Hadley Centre Coupled Global Climate Model	MM5 – PSU/NCAR Mesoscale Model
HaDCM3/ ECPC	Hadley Centre Coupled Global Climate Model	Experimental Climate Prediction Center
GFDL/ HRM3	Geophysical Fluid Dynamics Laboratory	Hadley Regional model 3
GFDL/ RCM3	Geophysical Fluid Dynamics Laboratory	Regional Climate Model version 3
GFDL/ECPC	Geophysical Fluid Dynamics Laboratory	Experimental Climate Prediction Center
Time slice GFDL	Geophysical Fluid Dynamics Laboratory	
Time slice CCSM	Community Climate System Model	

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Table 1. Combination of Global Climate Models (GCM) and Regional Climate Models (RCM) in the NARCCAP* Climate Models Adopted For This Study

3.1 Design Depth

3.1.1 Frequency Analysis

As per the *Hydrologic Criteria and Drainage Design Manual* of CCRFCD, a storm of a 6-hr duration and 100-yr return period (6h 100y) was used to design the stormwater infrastructure for the region. Thus, this study analyzed the effects of climate on rainfall events with a 6h 100y return period; this governed the design capacity of existing stormwater systems of the Gowan watershed. Design storm depths were calculated from 14 NARCCAP historic and future climate-model scenarios and one NARR historic climate model scenario at grid scale. A similar approach used by Forsee and Ahmed (2011) was adopted for the frequency analysis of the design storms. The climate model data used in this study were available in a 3 hourly temporal scale; thus, a 6-hour window through each 3 hourly data was used to convert the data into 6 hourly rainfall data.

According to a comprehensive study carried out by Bonnin et al. (2011) in the precipitation frequency atlas

of National Oceanic and Atmospheric Administration (NOAA), a generalized extreme value (GEV) probability distribution identified as the best representative distribution method for the region of this study area. This GEV probability distribution was used to calculate the 6h 100y design storms. Some previous studies (e.g., Mailhot et al., 2007; Kharin and Zwiers, 2000) used the GEV in their climate model studies as well. Moreover, the GEV method is an accepted frequency analysis in the non-stationary study of extreme parameters because of its ability to incorporate covariance and the skew nature of annual maxima data. Data from NARCCAP and NARR climate models were available in gridded forms of definite spatial resolution.

Regional frequency analysis (RFA) were used to increase the size of the data from the nearby homogeneous grids of the climate models. For this study, four encompassing grids of the centroid of the watershed were taken for the RFA. RFA was used as described by the *Flood Estimation Handbook* by the Institute of Hydrology, in the United Kingdom (IH, 1999) was used. RFA was based on the L-moment, a linear combination of probability-weighted moments that uses the surrounding grids to calculate the growth factor of the region. As was realized in some recent studies (Kendon et al., 2008), a study using multiple grids has an advantage over a study using a single grid. The regionalization eliminates the limitation of best-fit distribution associated with selecting only GEV methods by increased data. The three parameters for the GEV – i.e., location, scale, and shape – were calculated for the annual maximum data series using the L-Moments from Hosking and Wallis (1997).

The calculated historic 6h 100y design depths from NARCCAP model data were compared against the NARR 6h 100y design depths. During the assessment, the design depths from the NARCCAP model that were found to be greater than NARR design depth were eliminated. In the climate model data, the depth of the precipitation for each area was assigned using the area-averaged depth of the grid. Since the resolution – that is, the grid size of the NARCCAP (50 km) – was greater than NARR (32 km), the design depth from NARCCAP should be less than the NARR design depth. The depths from the NARCCAP models selected during assessment, along with NAAR data, were the only data used for further analysis. The Depth Area Reduction Factors (DARF), according to the CCRFFCD design manual (CCRFCD 1999) were used to convert the point design depth over the drainage area in each sub-basin.

3.1.2 Delta Change Factor

The delta change factor was used to transform the grid-scale climate information to the point observation. The ratio of the projected future design depth and the historic design depth provided the delta change factor for a particular NARCCAP model. For further analysis, two extreme delta change factors were used as the climate change factors. Only the NARCCAP models selected during NARR assessment were used to calculate the extreme delta change factors, which then were used with the existing design depth of the watershed to project design depths derived from climate change.

3.2 Hydrological Modeling

The EPA SWMM model was chosen to simulate the hydrologic response of the catchment. In recent versions of EPA SWMM, LID control modules have been added to simulate the hydrologic performance of source control techniques, such as permeable pavement, green roofs, rain gardens, and infiltration trenches (Rossman, 2015). In the EPA SWMM model, a combination of a vertical layer representing the LID options as well as the properties, thickness, void ratio, permeability, and underdrain characteristics were designated in terms of a 'per unit area' basis. The parameters of the EPA SWMM model for this study were taken from an existing model of the watershed, developed by CCRFCD, using the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) of the U.S. Army Corps. The same Curve Number infiltration loss method used in HEC-HMS also was used in the EPA SWMM model. The existing HEC-HMS models were part of the MPU that generated the hydrologic design parameters of the drainage system of the Las Vegas Valley. CCRFCD documented all the calculations of the hydrologic parameters, following the guidelines from the *Hydrologic Criteria and Drainage Design Manual* (CCRFCD, 1999). CCRFCD's official website (http://www.ccrfcd.org/) gives free access to all the data and models. Because CCRFCD divided the Gowan watershed into 231 sub-basins, this study used the same number of sub-basins as for the EPA SWMM model (Version 5.1.010).

This study used the existing design storm depths that were used to design the current drainage system, with the existing HEC-HMS model as a Baseline Scenario (BS), which does not consider the effects of

climate change. The delta change factors were multiplied with the baseline-scenario storm depths, and were assigned as Climate Change Scenario 1 (CCS-1) for the minimum delta-change-derived design depth and Climate Change Scenario 2 (CCS-2) for the maximum climate-change-derived design depth.

Three design storms were simulated in an EPA SWMM model generated for the region in the current land cover condition, as described by CCRFCD in their design. Then, two LID options, Permeable Pavement, and Green Roofs, were used to attenuate the excess runoff induced by climate change. These two options were selected based on the space available in the watershed, since other LID techniques – such as rain garden, green roof, vegetated swales, and bioretention systems – require open space, and cannot be used for other purposes later on. Probable LID-applicable areas were identified using the latest information regarding land use from Google Maps. The analysis showed that 59 out of 231 sub-basins were not suitable for the LID application; these sub basins included mountains, detention basins, and open lands. For a better interpretation of the effectiveness of LID options, the Adelson Sub-basin (0.62 km2) shown in Figure 1, which encompasses the Adelson Educational Campus, was selected for comparison with the LID options. The details of the two LID options adopted in this study are described as follows.

3.2.1 Permeable Pavement (PP)

A permeable pavement is a special type of pavement underdrain by a stone reservoir that allows water to pass through it, thereby decreasing the total runoff from a site and nearby areas (USEPA, 1999). The porous pavement helps to reduce the effluent to the main runoff by filtering through its layers. In the management of stormwater and mitigation of flooding, permeable pavements are considered a powerful tool. Generally, two types of surface layers, porous asphalt and pervious concrete, are used in permeable pavements. Many recent studies (e.g., Fassman and Blackbourn, 2010; Zhang and Guo, 2014) have recommended different types of permeable layers, with detailed analyses. The value of the parameters for the permeable pavement used in this study followed the nominal values recommended by the *Storm Water Management Model User's Manual Version 5.1* (Rossman, 2015) and by Rosa et al. (2015).

3.2.2 Green Roof (GR)

Green roofs are a typical tool of LID techniques, which cover roofs of buildings with vegetation. Urban roofs make a significant contribution to the increased peak flow during the rainfall. The rate and volume of the runoff can be reduced by implementing green roofs in urban watersheds in order to help manage the stormwater. Along with reduced runoff, green roofs have many other benefits, such as local urban cooling, creation of habitats for wildlife, and reducing air pollution. The advantages of a green roof are well documented in a number of published articles (e.g., Carson et al., 2013; Berardi et al., 2014). This study used nominal green-roof parameters as recommended by Rossman (2015) and Rosa et al. (2015).

4.0   Results

The results of this study consist of future design depths from the statistical analysis and hydrological modeling outputs using future climate scenarios in existing land use conditions as well as after implementing the LID conditions.

4.1 Design Storms

6h 100y design storms were calculated from 12 sets of GCM and RCM combinations and two time-slices of NARCCAP data, along with an NARR design depth; these depths are shown in Table 2. Historic and projected design depths for various climate models are shown in the second and third column of the table. The fourth column of the table shows the delta change factor for all the NARCCAP climate models considered in this study. The design depths were plotted, and compared in a scatter plot, as shown in Figure 2. The X-axis and Y-axis in the plot show the historic and projected 6 h 100 y depths, respectively, for the climate models under consideration. The vertical line in the plot corresponds to the NARR historic depth of 2.99 cm. Moreover, the diagonal line that divides the plot into two equal parts represents the line of the delta change factor equal to 1, which is defined as no change in the current and future climate scenarios. The plot above this diagonal line represents an increase in the future design depth, while the plot below this line denotes a decrease in future design depth of the watershed.

In assessing the NARCCAP depths with NARR depth, the NARCCAP combinations that were greater than the NARR historic design depth were eliminated. These eliminated NARCCAP combi-

Model	Historic 6h 100 y depth (cm)	Projected 6h 100y depth (cm)	Delta Change Factor
NARR	2.99	-	-
CGCM3/CRCM	1.95	2.15	1.11
CGCM3/ RCM3	3.80	3.76	0.99
CGCM3/WRFG	2.72	3.72	1.37
CCSM/CRCM	1.79	2.21	1.23
CCSM/WRFG	3.61	3.75	1.04
CCSM/MM5I	3.36	3.33	0.99
HaDCM3/ HRM3	2.98	5.81	1.94
HaDCM3/ MM5I	3.19	4.42	1.39
HaDCM3/ ECPC	3.23	4.59	1.42
GFDL/ HRM3	7.29	8.52	1.17
GFDL/ RCM3	5.15	7.17	1.39
GFDL/ECPC	6.72	7.17	1.07
Time slice GFDL	2.79	3.87	1.39
Time slice CCSM	2.62	2.98	1.14

*   North American Regional Climate Change Assessment Program
** North American Regional Reanalysis

Table 2. Historic and projected future design depths and delta change factors from NARCCAP* and NARR** climate models

nations fell on the right side of the vertical line of the plot in Figure 2. Six NARCCAP climate models were selected, and considered for the further study,

1.   The Third Generation Coupled Global Climate Model and the Canadian Regional Climate Model (CGCM3/CRCM),

2.   The Third Generation Coupled Global Climate Model and the Weather Research and Forecasting Model (CGCM3/WRFG),

3.   The Community Climate System Model and the Canadian Regional Climate Model (CCSM/CRCM),

4.   The Hadley Centre Coupled Global Climate Model and the Hadley Regional Model 3 (HaDCM3/HRM3),

5.   A time slice and the Geophysical Fluid Dynamics Laboratory (Time slice GFDL), and

6.   A time slice and the Community Climate System Model (Time slice CCSM)

Among the six climate models that were selected, there was a substantial difference in the delta change factor; this indicated various projections of future climate scenarios. Two NARCCAP model combinations, CGCM3/ RCM3, and CCSM/MM5I, predicted less severe future climates than other combinations; however, these two predictions were eliminated during NARCCAP model assessment, and were not considered for the further analysis. Considering that future climates are uncertain, this study took into consideration a range of future climate scenarios. Among the six NARCCAP climate models selected, the extreme delta change factors were 1.11 and 1.94 from CGCM3/CRCM and HadCM3/HRM3 NARCCAP models, respectively.
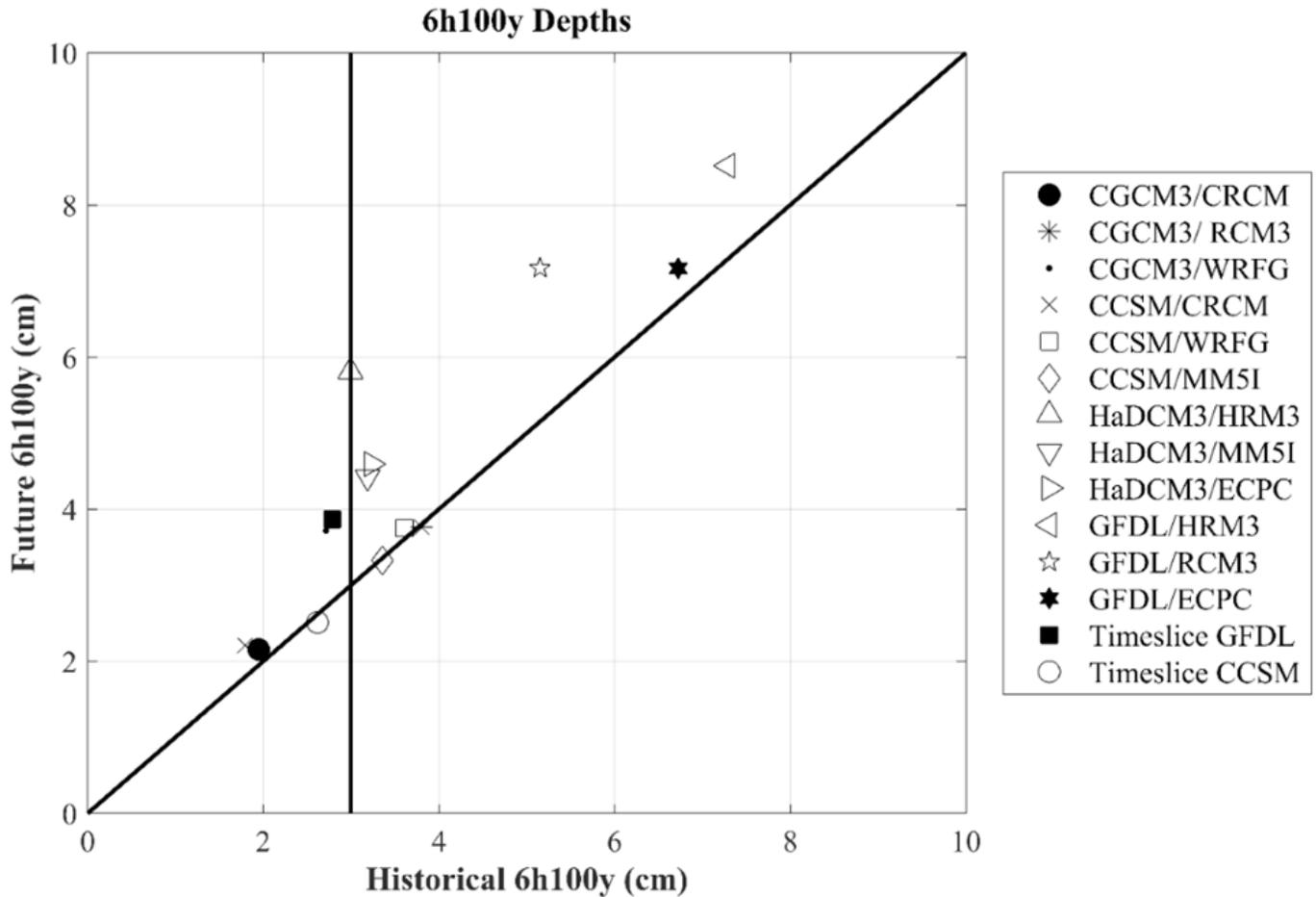
Figure 2. Scatterplot of NARCCAP 6h 100y design storms. The vertical line represents the NARR historical 6h 100y design depth; the diagonal line represents the line of 1 delta change factor (1:1 line, the 'no-change' climate condition); the NARCCAP 6 h 100 y depths above the 1 delta change factor line indicate a positive delta change factor (i.e., a projected increase in future design depth), and vice versa for depths below the 1 delta change factor line.

4.2 Simulation Outputs from Hydrologic Modeling

Three hydrological models in the EPA SWMM were simulated to analyze the effects on the stormwater infrastructure due to climate change, as follows:
1. Baseline Scenario (BS), with no change in the current design depth;
2. Climate Change Scenario 1 (CCS-1), corresponding to the projected design depth from a 1.11 delta change factor; and
3. Climate Change Scenarios 2 (CCS-2), corresponding to a projected design depth from a 1.96 delta change factor.

The outputs from the EPA SWMM modeling and the existing HEC HMS models had a slight variation due to the difference in the underlying rainfall to runoff transform methods. Thus, the EPA SWMM model was calibrated with the existing HEC HMS model in the different precipitation including the three climate scenarios. The calibration was carried out primarily adjusting the values of width of each sub basins. The width of sub basins represents the width of the overland flow path in the calculation of sheet flow runoff, and these values are initially calculated by dividing the area of a sub basin by the mean of the maximum overland flow length (Rosa et al., 2015). As per the user manual of EPA SWMM (Rossman, 2015), the width of the sub-basins should be adjusted for better compliance between the observed and simulated peak flows and runoff volumes. The fitness of the model was assessed by using the Nash Sutcliffe method, and values above 0.5 were considered for the acceptance limit.

Table 3 shows the hydrologic simulation results after calibration of the EPA SWMM model for the Adelson

sub-basin. In simulating LID-implemented conditions, this sub-basin was transformed to model the LID options, that is, 1) permeable pavement for 14% of the area, which includes parking lots and 2) 31% of the area for a green roof. The 6h 100y design storms for the three scenarios were distributed as per CCRFCD's Hydrological Design Manual (CCRFCD 1999), as depicted in Figure 3. Values for the depth area reduction factor (DARF) were used in all of the sub-basin in order to comply with HEC-HMS modeling and the CCRFCD design standard. The value of 0.99 for the DARF ratio was used in the design depths for all three scenarios of the Adelson Sub-basin in the EPA SWMM simulation. The DARF values and the types of storm distributions

| | | Peak Flow | | |
| | | | With LID | |
Scenarios	Without LID	Permeable Pavement	Green Roof	Combined
BS	10.96	-	-	-
CCS1	12.27	8.49	8.33	5.23
CCS2	22.38	15.45	15.08	9.47

Table 3. Simulation results of the EPA SWMM model for the Adelson Sub-Basin for BS, CCS1, and CCS2, with and without LID options
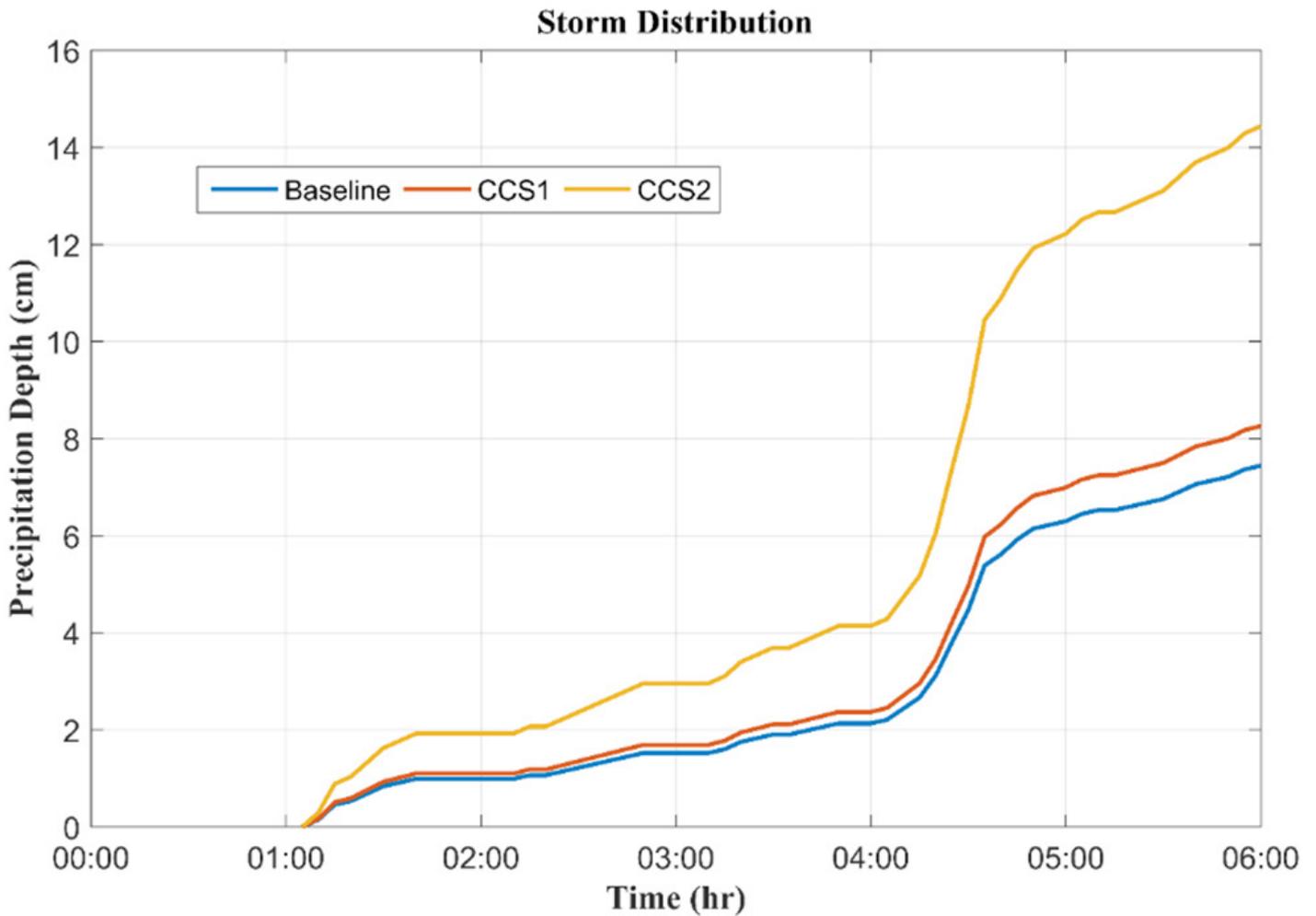

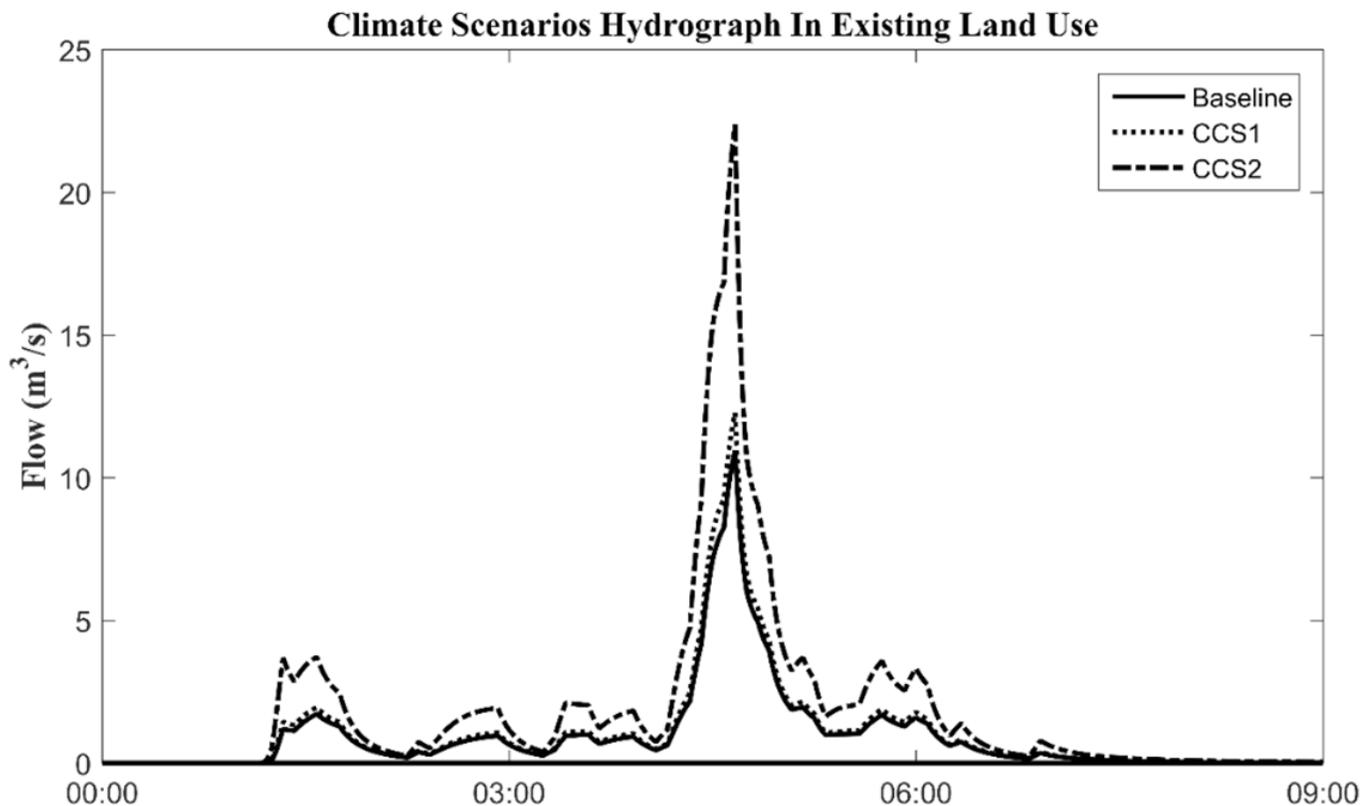**Figure 3**. Storm distribution for BS, CCS1, and CCS2 scenarios.

Figure 4. Hydrograph results for the EPA SWMM model of the Adelson Sub-basin for design storms in the BS, CCS1, and CCS2 scenarios under current land-use conditions.

were recommended in the Hydrological Design Manual as per drainage area. This manual followed DARF and storm distribution standard suggested by the Atlas of National Oceanic and Atmospheric Administration (NOAA), which were upon a comprehensive study of historic storms over western United States.

Figures 4 and 5 represent the graphical hydrograph results from the EPA SWMM simulation for BS, CCS1, and CCS2 for the Adelson Sub-basin. Results showed that this sub-basin generated 1.12 times more peak flow in CCS1 and 2.04 times more peak flow in CCS2. In the LID implemented simulation, a permeable pavement reduced peak flow by the same factor, 1.44, as for CCS1 and CCS2. Similarly, green roofs reduced the peak flow a factor of 1.47 and 1.48 for CCS1 and CCS2, respectively. The combined simulation used both LID options, permeable pavement and green roof, resulted in 2.34 and 2.36 times reduction in peak flow.

Figure 6 shows the total reduction percentage of peak flow for three LID conditions, permeable pavement, green roof, and a combination of permeable pavement and green roof. The percentage of reduction in the peak flow varied in each sub-basin. The north-

ern part of the Gowan watershed mostly consists of the mountainous areas, for which the LID options are not applicable; therefore, sub-basins in these areas had no effects from the LID options. The sub-basins that were moderately urbanized had the fewer areas applicable to LID options, which decreased the reduction percentage of the peak flows. Overall, the sub-catchments of the most urbanized areas had a similar response as for the Adelson Sub-basin, in which the reduction percentages varied between 25% to 35% for both the cases involving either permeable pavement or green roof. A 45% to 65% reduction in peak flow was found in the combined application of the permeable pavement and green roof.

5.0   Discussion

The statistical result for 6h 100y design storms showed a significant variation among the different combinations of the NARCCAP model. The variation became apparent since the GCM and RCM used in the NARCCAP model combinations differed substantially in terms of formulation and parameterization. This emphasizes the projection uncertainty from climate
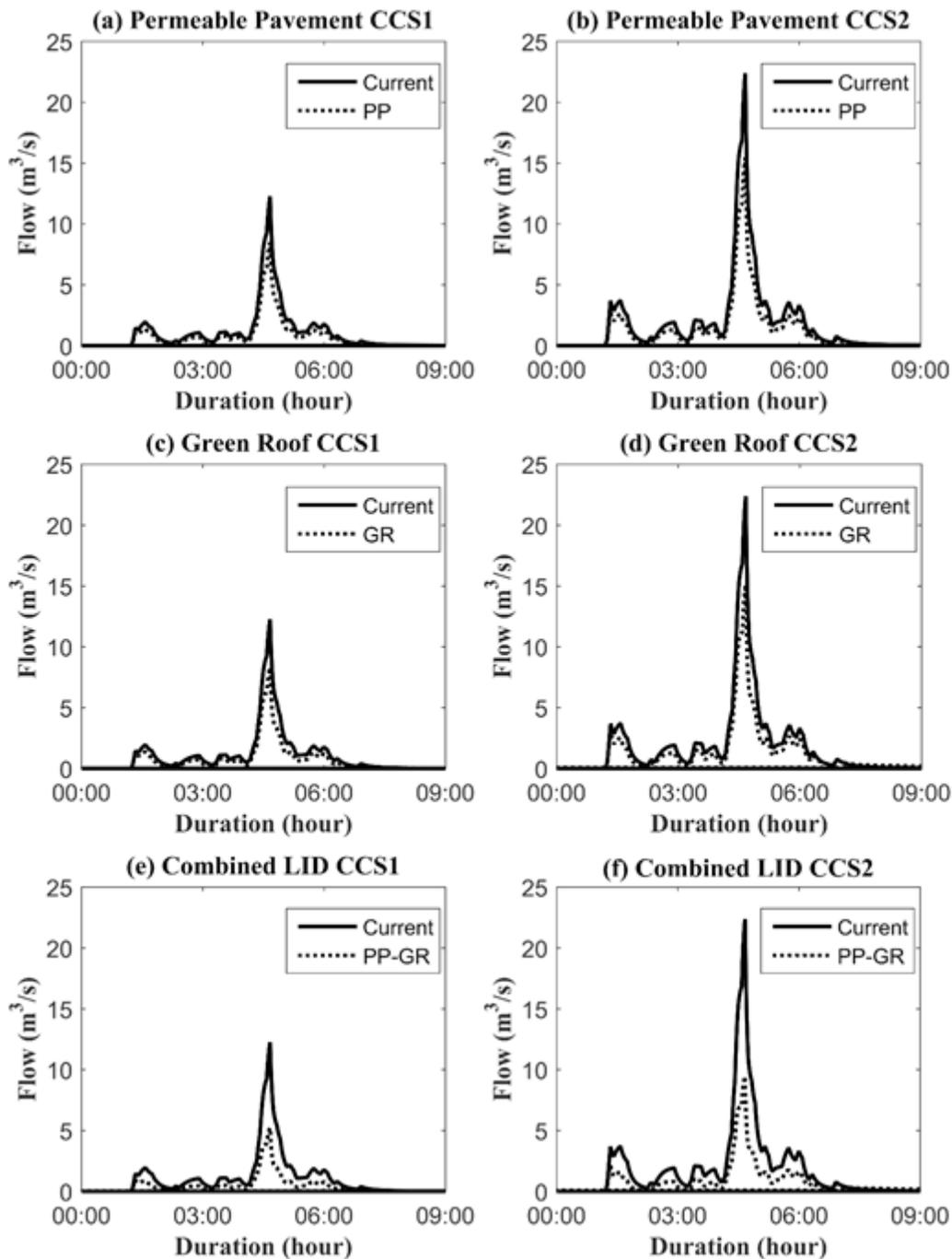
Figure 5. Hydrograph results for the EPA SWMM simulation for design storms of the Adelson sub-basin for the BS, CCS1, and CCS2 under current land-use conditions as well as with Low Impact Development (LID) implementations. Figures 5a and b show the Permeable Pavement (PP) LID option; 5c and 5d show the Green Roof (GR) LID option; and 5e and 5f show the combing PP and GR LID options.

models that rely on three primary sources, internal variability, model response, and forcing (Deser et al., 2012).

The predicted delta change factor for the models varied with each NARCCAP model. Two climate models showed a decrease in the future design depth of the region while the other 12 models showed an increase in future design depths during a changing climate. The estimated change in design depth from all 14 climate models varied from a decrease by approximately 1% to an increase by approximately 95%. The climate mod-
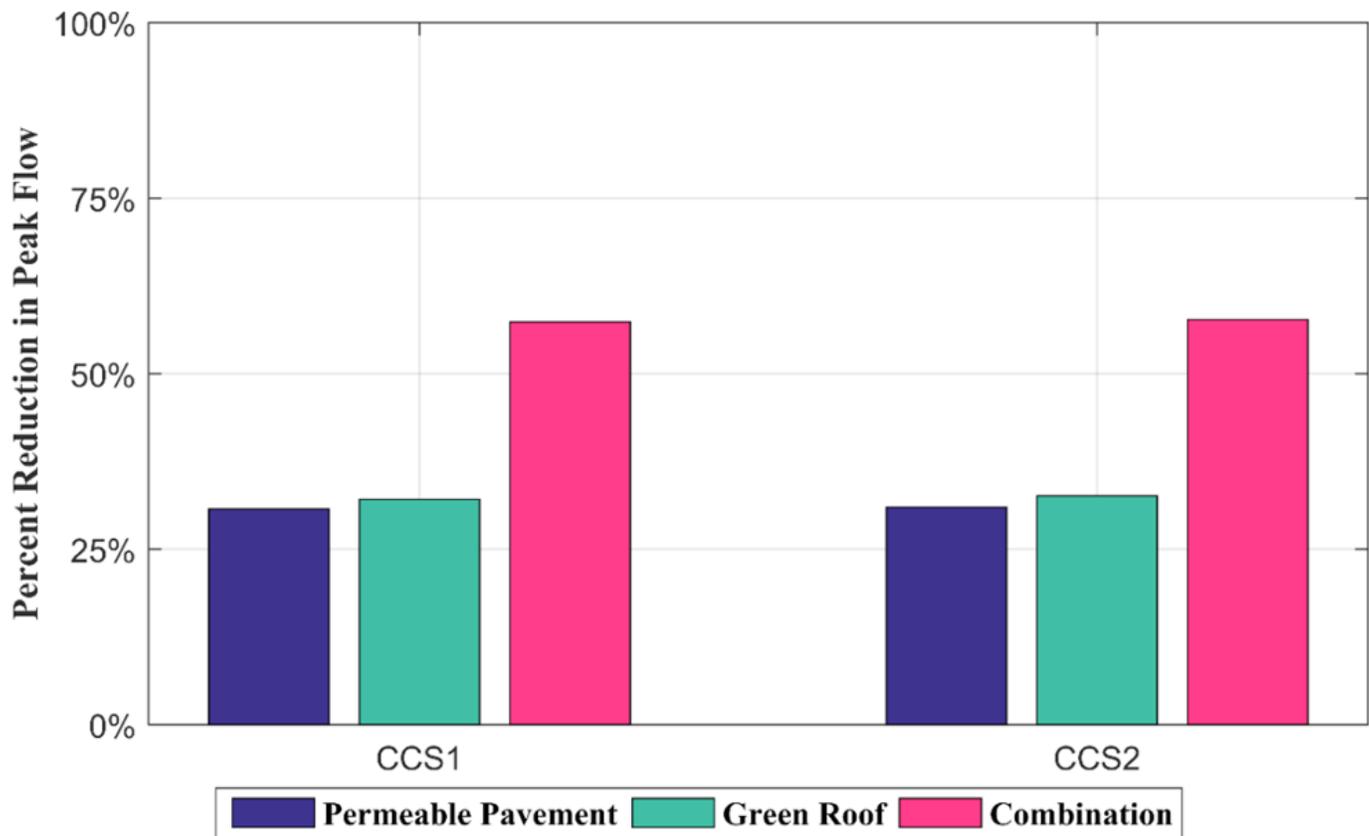
Figure 6. Graphical representation of a reduction in peak flow for the three LID options: PP, GR, and 3) a combination of PP and GR for CCS1 and CCS2.

els selected for the study ranged from an increase of approximately 11% to an increase of approximately 95%.

This study only considered the probable changes in future 6h 100y rainfall events. The current MPU (CCRFCD, 2013) followed the CCRFCD manual and used 6h 100y rainfall events for the design of existing stormwater systems (CCRFCD, 1999). The objective of this paper was to provide adjustment factors for the existing stormwater infrastructures due to climate change. Thus, the research focused on probable changes in the design storm, i.e., 6h 100y; using another return period would not have provided any comparative analysis. The same statistical approach could be used to determine the climate change effects on rainfall events of different durations and return periods.

Many previous studies (e.g., Kunkel et al., 2003; Guilbert et al., 2015) found an increasing trend in the intensity of extreme rainfall in the United States; this matches with the findings of this study. A study by Zhu et al. (2012) found a potential alteration in the intensity duration frequency (IDF) curve in six regions of

the continental United States; in most of the study area, an increase in future extreme events was determined. Coulibaly et al. (2005) did a study in the Grand River region of southern Ontario and the Kenora and Rainy River regions in northwestern Ontario in Canada, using a climate model simulation; they found a striking increase in the precipitation depths during future time periods. Mailhot et al. (2007) performed a study on the potential effects of climate change in the IDF curves for Southern Quebec, Canada, using a climate model projection. They found that in the future climate simulated by the Canadian Regional Climate Model (CRCM), the return period would around half for 2-hr and 6-hr storm events and decreased by one-third for 12-hr and 24-hr storm events.

A conventional drainage system uses the best management practices for floodwater management. Forsee et al. (2011) concluded that with the changing climate, the present stormwater system would surpass its capacity in simulated future scenarios of a climate model. In earlier studies on stormwater, Rosemberg et al. (2010)

and Semadeni-Davies et al. (2008) indicated the severity of combined effects of climate change and urbanization. These studies highlighted the need for measures necessary to reduce the harshness of climate change and urbanization effects in stormwater infrastructures.

LID techniques that were adopted in many previous studies were implemented in this study for the attenuation of excess runoff due to climate change in an urbanized watershed. In this study, the EPA SWMM hydrological simulation showed that permeable pavement can attenuate approximately 31% of the peak flow and green roofs can reduce the peak flow by approximately 33%. When these two LID techniques are applied together, approximately 57% of peak flow could be reduced. With the increased pressures of climate change as well as increased urbanization, the application of LID options is deemed to be a better solution. Damodaram et al. (2010) realized the effectiveness of LID techniques in their study. However, in dry and hot places like the Las Vegas Valley, the implementation of green-roof techniques needs special considerations when selecting roofing materials and methods. Milburn et al., (2011) conducted a study on green roofs in the Valley that adopted multiple construction practices that suited an urban desert climate. The performance of these roofs varied according to the inherent design practice. Proper design of green roofs for a desert environment consists of reducing irrigation requirements by adopting native plants, increasing the depths of the growing media, and drip irrigation techniques (USEPA, 2009).

6.0   Conclusion

This study explored the potential effects of climate change on the standard design depths and the possible remedial measures for the Gowan Watershed of the Las Vegas Valley. The present standard for stormwater design are unable to take into consideration the effects of climate change. Projections from NARCCAP models were used to evaluate future climate scenarios, which most studies suggest will be different from the present climate. A robust statistical method, with the aid of regionalization, was used to calculate the design storms. This method used nonstationary information of future climate scenarios into the existing stationary design framework.

This paper also analyzed the effectiveness of LID techniques on urban flooding. The overall conclusions drawn from this study are summarized as follows.

1.   The future design storms (6h 100y) from NARCCAP climate models for the Gowan Watershed will be increased by a factor of approximately 1.11, at minimum (from the CGCM3/CRCM NARCCAP model) to 1.94 at maximum (from the HadCM3/HRM3 NARCCAP model).

2.   In the hydrological simulation of a sub-basin, the projected design depth resulted an increase of approximately 12% in a minimum projection in peak flow and an increase of approximately 104% in a maximum projection in peak flow.

3.   Two LID techniques, Permeable Pavement and Green Roof, were found to be effective in attenuating the excess surface runoff induced by climate change when other LID options are limited.

4.   A 25% to 35% reduction in peak flow could be achieved in cases for each LID option, Permeable Pavement and Green Roofs.

5.   The combination of Permeable Pavement and Green Roof LID techniques can reduce the peak flow from approximately 45% to 65%.

6.   The severity of the combined effects of climate change and urbanization on the stormwater system could be reduced by using the LID techniques as described in this study.

7.   Hydrological modeling using EPA SWMM could be a convenient tool for other studies of urban watersheds for which LID techniques can be utilized.

The two LID techniques, Permeable Pavement and Green Roof, can be applied in an urbanized watershed where the increase in design storms due to climate change seem to be inevitable. This study provides some insight for water managers and decision makers by considering the effectiveness of LID options for the attenuation of floodwaters on a watershed scale. However, the tradeoffs between the LID options should be assessed thoroughly to strategically select and determine a reasonable level of implementation. Finally, the methods adopted in this study can be implemented elsewhere as management strategies to deal with the realities of climate change.

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