FIU | Sea Level Solutions Center

# Potential Implications of Sea-Level Rise and Changing Rainfall for Communities in Florida using Miami-Dade County as a Case Study


By: **Sea Level Solutions Center (SLSC), Florida International University (FIU)**

**Project Team:**
Dr. Jayantha Obeysekera, Ph.D., P.E. PI (Director, SLSC)
Dr. Michael Sukop, P.G., C.Hg. (Professor, SLSC, Co-PI)
Dr. Tiffany Troxler, (Director of Science, SLSC, Co-PI)
Michelle Irizarry, P.E. (SLSC Research Affiliate, Owner, Continuity, H2O)
Martina Rogers (Ph.D. student)

FIU Sea Level Solutions Center
FLORIDA INTERNATIONAL UNIVERSITY

# Final Report (June 10, 2019)

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Florida Department of Business and Professional Regulation
Florida Building Commission

and

Sea Level Solutions Center (SLSC), Florida International University (FIU)

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# Introduction

The Florida Building Code (FBC) is one of the strongest in the nation for protection from coastal hazards including wind and storm surge. Coastal communities are at risk of increased flooding due to variations in rainfall extremes, sea-level rise, and a rising water table exacerbating potential for flood damage to buildings. The Florida Building Commission awarded a contract to the Sea Level Solutions Center (SLSC) in the Institute of Water and Environment (InWE), Florida International University (FIU) to assess potential data updates used in Flood and Rain Loads that may lead to increased flood risk due to increasing sea levels and to ground water levels and rainfall extremes. The overall effort to assess flood risk may be accomplished by comparing existing flood elevations with new elevations based on updated rainfall data and sea-level rise projections. For the current contract, SLSC will evaluate groundwater level due to sea-level rise and changes in extreme rainfall in Miami-Dade County and potential implications for the current Florida Building Code (FBC). The initial effort will be focused on Miami-Dade County to establish an applicable model that can be applied for other areas across the State.

Sea Level Rise (SLR), and any changes to rainfall (both averages and extremes) have the potential to increase the flood elevations in several ways. Increased ocean levels due to sea level rise and storm surge will impact the efficiency of water control structures along the coast, primarily due to low topography in places such as Miami-Dade County. Potential increase in extreme rainfall will not only increase flood levels but also rain loads on buildings. Finally, rising water tables due to sea level rise and porous geology will increase the runoff volumes due to the decrease in storage typically available above the shallow water table. Detailed surface-water/groundwater models are required to determine the flood levels under such conditions and their development is beyond the scope of this study. However, this project provides quantitative estimates and simulations of future conditions that should be used as input for such modeling by agencies that have been historically charged with determining flood elevations, such as the Department of Environmental Resource Management (DERM) in Miami-Dade County.

The scope of the current effort included the following tasks:

**Task 1**. Development of average May-October groundwater level maps (used for evaluating flood risks) through groundwater modeling under future sea level rise scenarios.

**Task 2.** Updating Existing Rainfall Maps

**Task 3.** Evaluation of FBC-related requirements.

This report, including its appendices, provides a comprehensive presentation of work on the above tasks and the corresponding results. The research associated with the project was accomplished by the following team of investigators at FIU:

- Dr. Jayantha Obeysekera, P.E. (Director, SLSC, and Principal Investigator)

- Dr. Michael Sukop, P.G., C.Hg. (Professor, Co-PI)
- Dr. Tiffany Troxler, (Director of Science, SLSC, and Co-PI)
- Michelle Irizarry, P.E. (SLSC Research Affiliate, Owner, Continuity H2O, LLC)
- Martina Rogers (Ph.D. student)

The report is organized as follows. The work associated with Task 1: Development of average May-October groundwater levels maps under future sea level rise scenarios is presented in Section I. Task 2, covering the updates to rainfall maps, is described in Section II. Section III presents the recommended changes to the Florida Building Code (FBC) to reflect the findings of the work in this research project, including some recommendations for future code-related research. Detailed technical assumptions, methods, and results are provided in Appendices I through III.

# I. Development of average May-October groundwater level maps under future sea level rise scenarios.

According to the Scope of Work, this task required the following subtasks:

- FIU SLSC shall review and apply the existing Miami-Dade groundwater model (MODFLOW-based but with improved surface water routing capabilities) developed by the United States Geological Survey (USGS) for Miami-Dade Water and Sewer Department (WASD) to create wet-season (May through October) water-table maps. The maps will be produced using ArcGIS software to allow determination of water-table elevation for any location within the county.

- The Miami-Dade groundwater model developed for the WASD shall be executed for a future condition (approximately 2060-2069 to capture a condition approximately 50 years from now) using existing and future rainfall scenarios. This particular future condition is the same as what has been used in Broward County and by using the same period, consistency between the two counties will be ensured. Future ocean boundary conditions reflecting sea level rise for modeling shall be obtained from the Unified Sea Level Rise Projections developed by the Southeast Florida Regional Climate Change Compact.

- FIU SLSC shall evaluate various climate model outputs to determine potential changes in rainfall under future conditions. Other input parameters shall remain the same as in the calibrated model to be provided by WASD. Once the modeling scenarios (sea level rise and rainfall) are completed, the simulated water table data shall be analyzed for the months of May through October to develop the spatial maps of water table elevation for the entire modeling domain.

## Methodology

Development of future conditions (2060-2069) involves updates to several inputs to the Miami-Dade MODFLOW model. They include (a) potential change in land use and the corresponding changes to directly connected impervious areas and to aquifer properties in areas with additional quarry lakes; (b) future ocean boundary conditions that reflect sea level rise; (c) future potential rainfall patterns; and (d) future Everglades water levels reflecting implementation of the proposed restoration projects. The updated information was then used as inputs to a well-designed set of scenario runs to develop groundwater level maps. A few sensitivity runs were also made to investigate implications of some of these changes and well-field pumpage. The model was run for the period 2055-2069 to allow a 5-year warm-up period at the beginning of the simulation, which was not considered in the subsequent analyses.

## Groundwater Model

The SLSC team used the groundwater model developed by USGS for the Miami-Dade Water and Sewer Department known as the Urban Miami-Dade Model (UMD) (Hughes and White, 2016). The UMD was produced through a cooperative partnership between Miami-Dade County and the United States Geological Survey. It serves a de-facto role as the County's groundwater model-of-record.

UMD is the most comprehensive model known to exist at the whole-county scale and includes many processes. Perhaps most important of these is its linkage to a surface water routing model (SRW1, Hughes, et al., 2012) designed to simulate the region's extensive canal system and its water level control structures. The canals exert a controlling influence on the water table position and are operated with the dual purposes of flood control and to protect well fields from saltwater intrusion.

The model was originally designed to operate into a 30-year future. Many of the processes it simulates needed to be partially and/or wholly re-worked to properly simulate more distant futures (2060-2069) when infrastructure – particularly canal water control structures and in some instances, canals and coastal areas themselves – may be inundated.

A decision was made to begin the model development starting from the peer-reviewed and published version of the code and associated datasets made available by USGS. A review of the model and the data sets revealed that significant numbers of datasets needed updates. Initial effort required to implement the model required the installation of the model code, pre- and post-processing software written primarily in Python language on the computers at FIU. Development of future conditions for simulation runs are described in detail in Appendix I. A summary of the input updates is as follows:

### Future Land Use

The future scenarios previously simulated by the USGS with the Miami-Dade MODFLOW model used 2008 land use data to develop direct surface-water runoff, agricultural water demand, recreational irrigation, and monthly crop coefficient values (Hughes and White, 2016). However, for this project, 2030 predicted land use from the Adopted 2020-2030 Comprehensive Development Master Plan (CDMP) for Miami-Dade County were obtained. The predicted land use for 2030 was assumed to represent the built-out condition circa 2060. The land use map was also modified by adding the 2018 permitted extents of quarry lakes in the county. Changes in the impervious areas due to modifications in the land use map were also made to reflect the increase in Directly Connected Impervious Area (DCIA) fractions in each model grid cell. Detailed categorizations of open water, agricultural, and natural land uses beyond those in the CDMP were also incorporated into the model grid from SFWMD's 2018 permitted land use dataset. To account for the existence of additional quarry lakes in 2030 land use (based on 2018 permitted quarry lake coverage) compared to the 2008 land use (which assumed 1999 quarry lake coverage), the groundwater properties at quarry lake cells were modified for the future scenario model.

## Future Ocean Boundary Conditions

The original model used actual daily average water levels at the ocean boundary that included astronomical tides, storm surge, waves, and sea level rise at the time of its development as measured at NOAA primary harmonic station 8723214 in Virginia Key. However, for the update, it is not possible to forecast future total water levels (including storm surge and waves) for 2060-2069 and a decision was made to use only the astronomical tide plus sea level rise predicted for that period. Daily tidal predictions were made using the water levels at Virginia Key. Since the final product of this project is to produce an average of groundwater levels over the wet season months, the use of only the future astronomical tides (including the projected sea level rise) was deemed appropriate. A sensitivity analysis demonstrated that the use of astronomical tides alone was adequate for computing average wet season groundwater levels.

Future (2055-2069) ocean boundary conditions reflecting sea level rise for modeling were obtained from the Unified Sea Level Rise (SLR) Projections developed by the Southeast Florida Regional Climate Change Compact (2015) for both the IPCC AR5 RCP8.5 Median curve and the USACE High curve. These future conditions reflect the effect of sea level rise on the predicted tides (based on harmonic analysis and fitting) for the two selected SLR scenarios.

## Future Rainfall

The study considered the potential change in future rainfall patterns, as that would affect groundwater recharge and hence the future groundwater levels. Previous studies at the South Florida Water Management District (SFWMD) have shown that the rainfall projections made using global and regional climate models have significant biases. Consequently, bias correction was necessary before the climate model results could be used. Based on the best available data at the time of this study, the bias-corrected Localized Constructed Analogs (LOCA) dataset produced by University of California at San Diego was selected as input to the groundwater model under future conditions. Statistically-downscaled daily rainfall time series from 30 climate models in the LOCA data sets were evaluated for selecting a representative future rainfall input. The biases of the annual and wet season total rainfall were computed using the gridded historical dataset produced by the SFWMD for the period 1991-2005. Many climate models showed a negative bias. The bias in mean rainfall was first corrected by using a simple ratio. The suite of model datasets, after bias correction, showed both negative and positive changes from the historical period to the future period (2055-2069). The study considered the potential for increased rainfall in the future and therefore selected a rainfall time series from a model with small bias but with a increased-rainfall rank of about 95% among all models. This is approximately equivalent to the 95% percentile. The selected model showed about 8% increase in both annual and wet season rainfall amounts. As input to the MODFLOW model, a gridded rainfall dataset corresponding to 2055 to 2069 was produced using a technique known as Multiplicative Quantile Delta Mapping (MDQM, TetraTech 2015).

## Future Everglades Water Levels

Future water levels in the Everglades are expected to be different from the historical period due to future implementation of the Comprehensive Everglades Restoration Plan (CERP). Water levels will also change due to potentially higher rainfall as a result of climate change. To select a representative future water level condition, simulated water levels in the Everglades for two modeling scenarios produced by the South Florida Water Management District were evaluated: (1) the updated full-CERP implementation (CERP0 scenario which uses projected future land use, historical rainfall, and includes CERP restoration components such as partial decompartmentalization of Water Conservation Area 3 (WCA3) and Everglades National Park (ENP), Water Preserve Areas, Lakebelt Storage, etc.); and (2) A current baseline scenario with 2010 land use and a 10% increase in rainfall. Based on the availability of data, water levels from the CERP0 scenario with historical rainfall were chosen for the future (2055-2069) modeling scenario. The average simulated water levels from this run for each day of the year (1-365) at each of the Everglades/WCA grid cells were repeated for each year in the future simulation period, 2055-2069. This was deemed a reasonable approximation to the future water levels in the Everglades.

## Future Scenario and Sensitivity Runs

The Miami-Dade MODFLOW model is a peer-reviewed model developed by the USGS (Hughes and White, 2016) that includes the Surface-Water Routing (SWR1, Hughest et al., 2012) package to simulate surface water discharges, and surface water/groundwater interaction. It also uses the Sea Water Intrusion (SWI2, Bakker et al., 2013) Package to simulate saltwater intrusion into the surficial aquifer. As part of this project, we performed two main future scenario runs and three additional sensitivity runs using the calibrated Miami-Dade MODFLOW model developed by the USGS (Table 1). The future scenario and sensitivity runs simulated the period 2055-2069 with the intent of using the first five years (2055-2059) of the simulation as a spin-up period and dropping them from the analysis.

### *Modeling Assumptions*

The following are common assumptions in all five (5) future scenario and sensitivity runs:

- 2030 land use and directly connected impervious areas, 2018 permitted quarry lakes, calibrated crop coefficients
- 2010 septic return flow from the USGS scenarios
- The western boundary condition consists of water levels in Water Conservation Area 3 (WCA3) and Eastern Everglades National Park (ENP) from CERP0 South Florida Water Management Model run (average for Julian day at each cell is repeated every year)

- The surface water network, structures, and their effective gate openings remain the same as in the USGS 1996-2010 calibration/verification of the model.

The two main scenario runs (Runs 1 and 2 in Table 1) are identical except that they use two different tidal boundary conditions that represent tidal predictions plus two different sea level rise curves (IPCC AR5 RCP8.5 Median curve, and USACE High curve, respectively). Runs 3-5 are variations of the first two runs. All runs, with the exception of Run 3, use 2030-2040 wellfield pumpage from USGS Scenario 1 for Miami-Dade Water and Sewer Department (MDWASD) wells (372.58 MGD), and 2010 wellfield pumpage for other wells (52.65 MGD) for a total wellfield pumpage of 425.23 MGD. Pumpage at a particular wellfield was distributed equally among all wells in that wellfield and a daily pumpage timeseries representing 2030-2040 conditions is repeated during every year of a scenario run. All pumpage is extracted from the bottom layer of the model (Layer 3), which is the primary production zone for the Biscayne Aquifer in this area.

Run 3 is a worse-case scenario for flooding (i.e., highest water table elevation) due to its use of a high SLR curve and no wellfield pumpage. The main future scenario runs (Runs 1 and 2) use a rainfall time series from a bias-corrected LOCA model with increased rainfall when compared to historical conditions, and assume a 5% increase in reference evapotranspiration (RET) resulting from increased future temperature. Runs 4 and 5 are the same as 1 and 2, but using historical rainfall and RET.

In order to provide a representative set of initial conditions for modeling these scenarios, three long-term simulations for the period 1996-2054 were performed. The initial location of the saltwater/freshwater interface in 2055 is critical and difficult to derive from analytical methods. The simulations were broken into three periods (1996-2025, 2026-2040, and 2041-2054). The long-term simulations were based on a repetition of the stresses (rainfall, RET, irrigation, wellfield pumpage, structure operations) during the 1996-2010 calibration/verification period; however, the eastern boundary condition at Virginia Key was based on future tidal predictions plus sea level rise along one of the two SLR curves of interest (IPCC AR5 RCP8.5 median or USACE High SLR curves).

*Table 1. Assumptions for two main scenario runs (1 and 2) and the three additional scenario sensitivity runs (3-5).*

| **Run short-name** | **(1) LOW SLR** | **(2) HIGH SLR** | **(3) HIGH SLR + NO PUMPAGE** | **(4) LOW SLR + HIST RAIN/RET** | **(5) HIGH SLR + HIST RAIN/RET** |
|---|---|---|---|---|---|
| **Run description** | **Low SLR scenario (IPCC median)** | **High SLR scenario (USACE High)** | **High SLR scenario with no pumpage** | **Low SLR scenario with historical rainfall/RET** | **High SLR scenario with historical rainfall/RET** |
| **Rainfall and recharge** | | | | | |
| 1996-2010 NEXRAD rainfall with 1.05 correction factor | | | | X | X |
| Bias-corrected LOCA rainfall for 2055-2069 (no correction factor applied) | X | X | X | | |
| **Reference evapotranspiration (RET)** | | | | | |
| 1996-2010 RET from the USGS | | | | X | X |
| 1996-2010 RET from the USGS with 1.05 adjustment factor due to future temperature increase | X | X | X | | |
| **PWS pumpage** | | | | | |
| No pumpage | | | X | | |
| Future Pumpage as in USGS Scen. 1 for 2030-2040 | X | X | | X | X |
| **Tidal boundary condition** | | | | | |
| Predicted sea levels for 2055-2069 + SLR from IPCC AR5 RCP8.5 median curve | X | | | X | |
| Predicted sea levels for 2055-2069 + SLR from USACE High curve | | X | X | | X |

## Results

Modeling results are summarized in terms of three major variables: (1) wet season average groundwater levels in the top layer of the model, (2) wet season average depth to the groundwater table, and (3) the spatial location of the freshwater/saltwater interface at the bottom of each of the three model layers at the end of the last dry season (May 31$^{st}$) in the simulation. These results are presented (Appendix I) as absolutes as well as differences from the calibration/verification run (1996-2010) for the 10-year period from 2060-2069. Differences between the sensitivity runs and the two main scenario runs are also presented in Appendix I. Wet season (May-October) averages are over 2,760 simulation days in the calibration/verification run, and over 1,840 days in the future scenario and sensitivity runs.

The final maps of future (2060-2069) wet season average heads and the depth to water table maps are shown below for (1) Low Sea Level Rise Scenario (Figure 1), (2) High Sea Level Rise Scenario (Figure 2); (3) High Sea Level Rise Scenarios with no pumpage in wellfields (Figure 3). The increase in average wet season water table from the calibration period to future is shown in Figure 4.

**Wet season average heads (ft NAVD88) LOW SLR (2060-2069)**

**Wet season average depth to water table (ft) LOW SLR (2060-2069)**

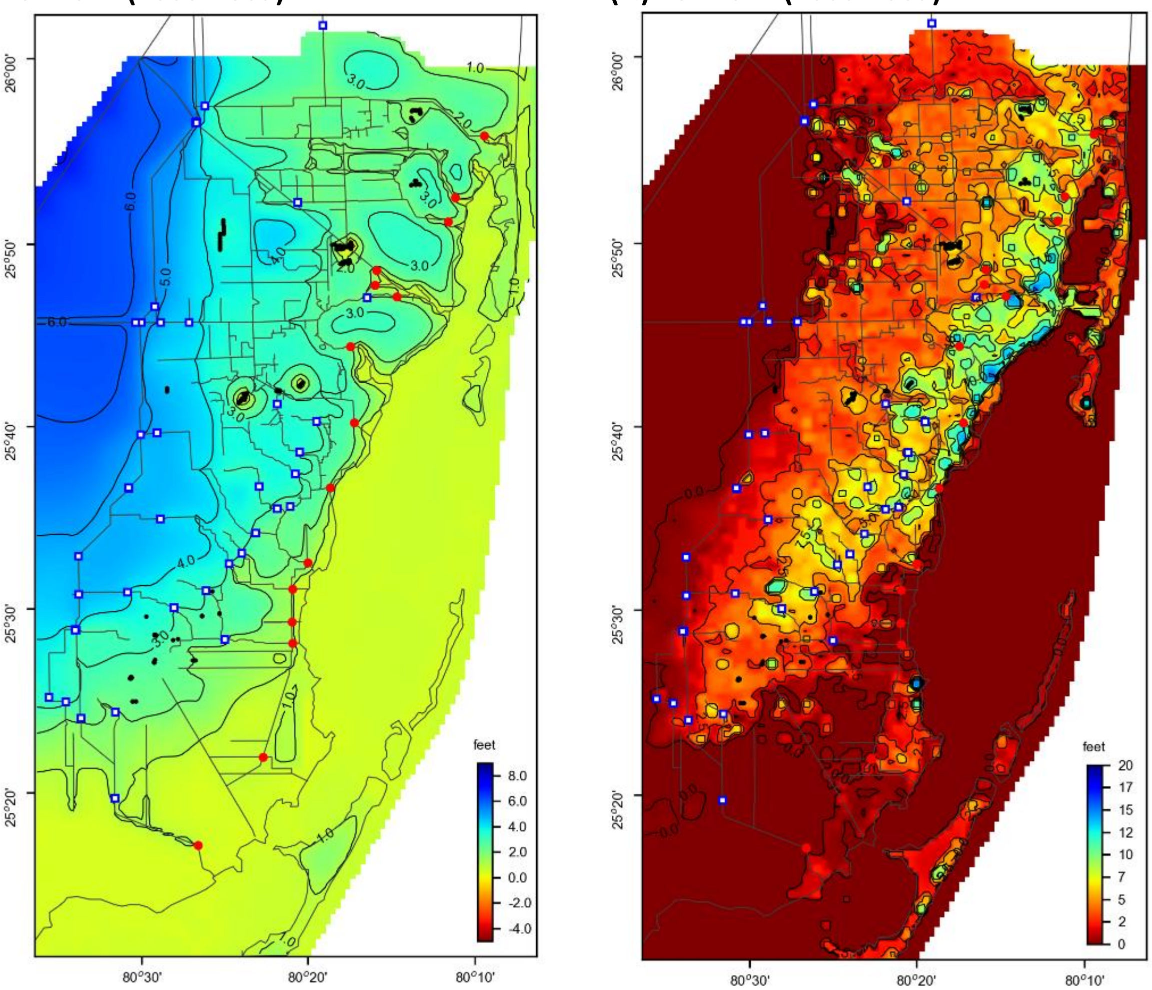


*Figure 1. Average wet season heads (ft NAVD88) (left panel) and the average wet season depth to water table (ft) (right panel) for the Low SLR scenario*

**Wet season average heads (ft NAVD88) HIGH SLR (2060-2069)**

**Wet season average depth to water table (ft) HIGH SLR (2060-2069)**

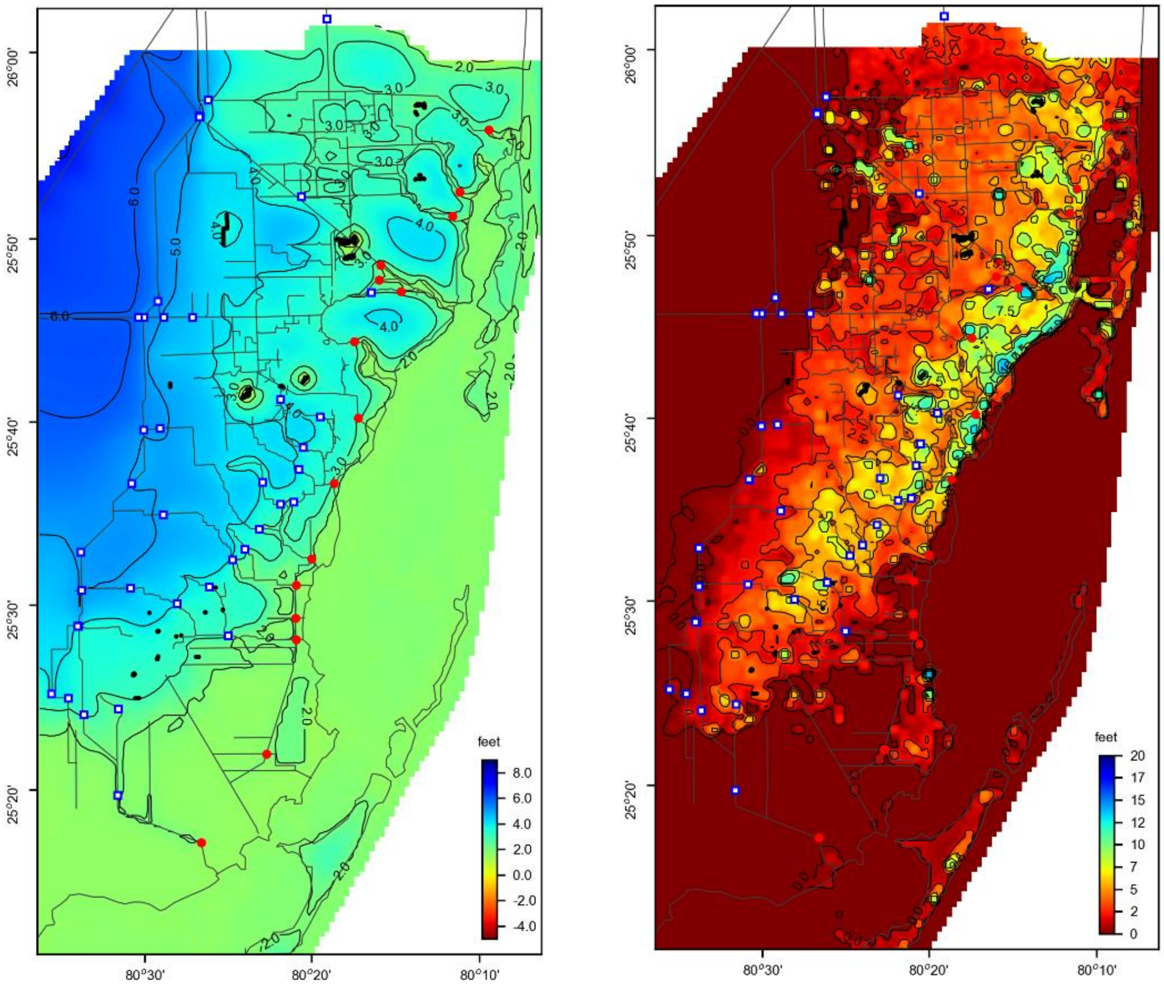


*Figure 2. Average wet season heads (ft NAVD88) (left panel) and the average wet season depth to water table (ft) (right panel) for the HIGH SLR scenario*

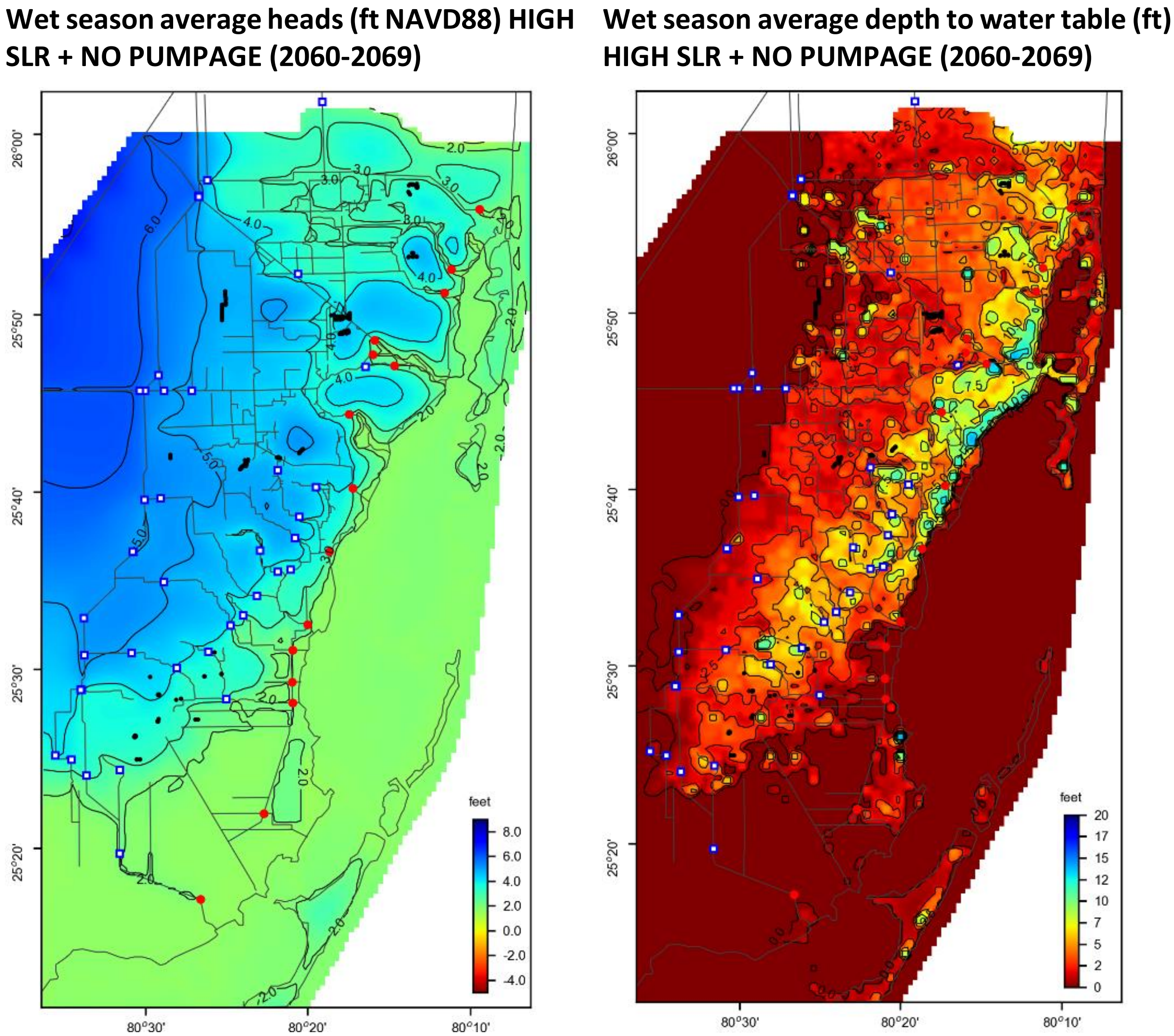


*Figure 3. Average wet season heads (ft NAVD88) (left panel) and the average wet season depth to water table (ft) (right panel) for HIGH SLR + NO PUMPAGE sensitivity run.*

**Difference in wet season average heads (ft) LOW SLR - CALIBRATION**

**Difference in wet season average heads (ft) HIGH SLR - CALIBRATION**

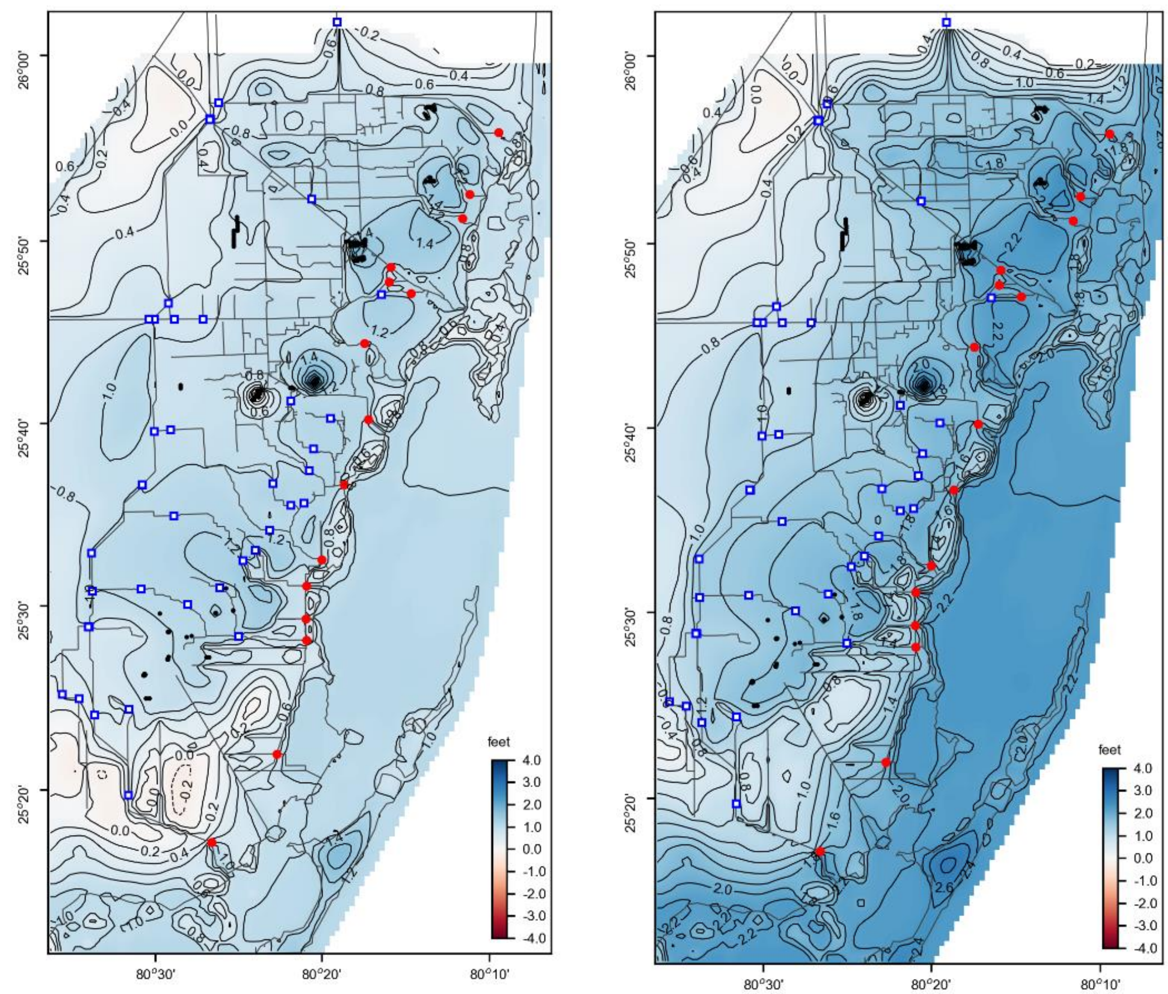


*Figure 4. Difference in average wet season heads (ft) for LOW SLR (left panel) and HIGH SLR scenario (right panel)*

## *Discussion*

Prediction of infrastructure improvements and changes in water management decades out into the future to account for climate change and sea level rise is extremely challenging. There are no strategic plans developed by the regional and local governments that we could use for configuring what the system may look like by mid-century or later. Sea Level Rise, particularly the high scenario, has the potential to permanently inundate large parts of the coastal area of Miami-Dade County (see maps in Appendix I). How the communities may react in terms of retrofits and or redevelopment in these areas is highly uncertain. However, this physical reality must be considered in modifications to the Florida Building Code. In addition, the regional flood control system, built during the middle of the last century, may require large-scale retrofits or reconstruction to accommodate higher ocean levels. The flood control system may also require new operational rules as opposed to the historical operations assumed in this study. Effectively, the modeling assumed that the regional flood control system will have adaptation to sea level rise implemented by 2060 that would permit it to function in a similar manner as it does now. That may require moving salinity control structures upstream and raising major levees and/or sea walls along primary canals. Future modeling could include additional adaptation measures such as increased flow capacity at structures and forward pumping at coastal salinity structures.

The maps shown above and in Appendix I were used as the basis for recommendations to the code (see recommendations in Section III). Taking a conservative approach, the maps corresponding to the high sea level rise scenario with no pumpage (which results in the highest groundwater levels) could be considered as criteria for future building codes. Alternatively, the spatial increase in the groundwater levels (Figure 4 above) may be added to any existing average water table maps for the FBC where relevant. See Appendix I for some caveats.

Elevated water table due to sea level rise will reduce the soil storage available for absorbing initial amounts of rainfall during an extreme event such as the 100-year storm. We calculated the loss of soil storage by 2060-2069 as the product of specific yield in the top layer of the aquifer and the net increase in water table elevation. The spatial map of the loss of the soil storage during the wet season is shown in Figure 5. The storage loss is in the range of 2 to 10 inches and it is spatially varying. Because the increase in groundwater level is higher near the coast, the storage loss is higher in that vicinity. The exact effect of the decrease in soil storage on initial loss of rainfall storage capacity and thus base flood elevation requires detailed modeling of the surface water system in Miami-Dade County. The current base flood elevations (Static BFEs) are shown in Figure 6 and it should be noted that the elevations shown in this figure are in ft. NGVD. It is the project team's understanding that the county is conducting such modeling using the XP-SWMM model to update inland flood elevation maps. It is our recommendation that the county use Figure 5 as a tool to determine the effect of rising water table elevation on the flood elevations and hence the BFE. Increased rainfall excess (in the range of 2 to 10 inches) will need to be routed through the drainage system to determine the corresponding increase in flood levels.

**Difference in wet season soil storage**
**HIGH SLR – CALIBRATION (inches)**

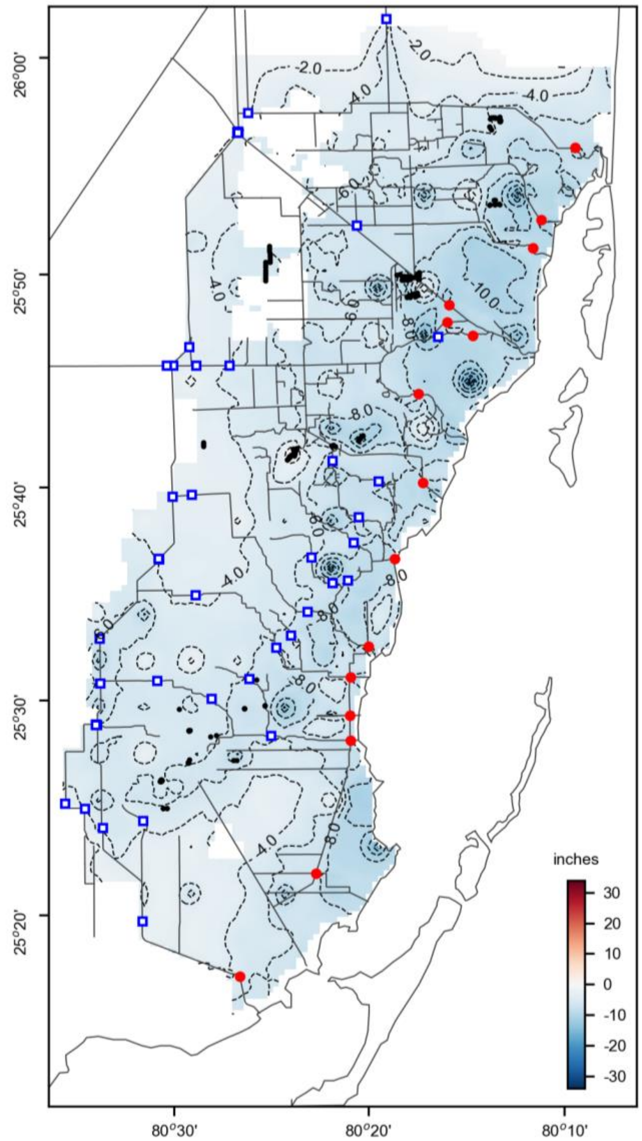


*Figure 5. Decrease in soil storage above the water table for the high SLR Scenario*

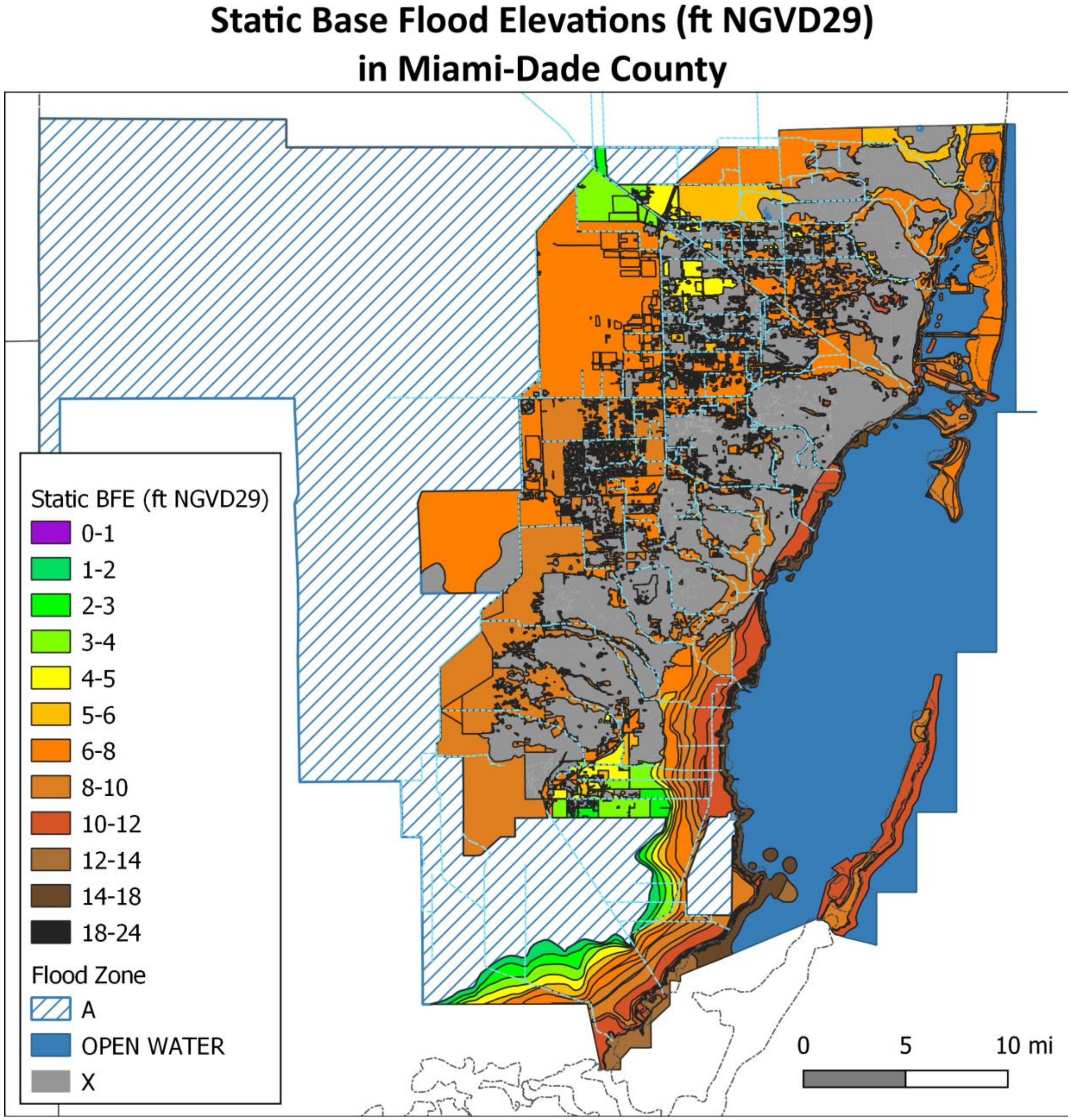


*Figure 6. Current Static Base Flood Elevations (SBFE) (feet NAVD) for Miami-Dade County)*

## II. Updating Existing Rainfall Maps

This task required the following subtasks:

- FIU SLSC shall evaluate the most recent rainfall data and the studies available from South Florida Water Management District (SFWMD), National Oceanographic and Atmospheric Administration (NOAA), and other agencies (e.g., Miami-Dade County) to develop 100-year rainfall for durations of 1 hour up to 3 days. Based on this analysis, spatial maps of rainfall will be produced.

- FIU SLSC shall assemble a database of rainfall data up to Year 2017 and develop a time series of annual extremes for various durations of 1 hour up to 3 days.

- FIU SLSC shall use the extreme value analysis methods using the statistical software packages in R (popular statistical software package that is free) to determine the design rainfall magnitudes for 100-year return period for various durations. The resulting values shall be mapped across Miami-Dade County using appropriate spatial interpolation methods to produce the rainfall loading maps. For further validation of the maps, the rainfall loading maps shall be compared with the published data available from SFWMD and NOAA.

The FIU team evaluated the most recent rainfall data and studies available from the South Florida Water Management District (SFWMD), National Oceanographic and Atmospheric Administration (NOAA) and other agencies (e.g. Miami-Dade County).

### Historical Rainfall

The following historical rainfall data sets were acquired for this purpose.

1. Annual maximum series of precipitation from NOAA Atlas 14 for durations from 5 minutes to 60 days.
2. Daily and hourly data from the South Florida Water Management District (SFWMD)'s DBHydro database
3. Miami-Dade County rainfall data from Miami-Dade Water and Sewer Department (WASD)
4. Florida State University's COASP rainfall data
5. University of Florida's IFAS FAWN rainfall data
6. GROWER network rainfall data from IFAS

After a thorough quality check of all the historical data, only rainfall data from NOAA Atlas 14 Volume 9 and from SFWMD DBHydro database were used for this task. There were several duplicate stations, insufficient records, and quality concerns for many of the other historical datasets. The chosen rainfall stations were based on balancing the desire of using the most recent annual maxima rainfall data available and the desire of including sufficiently long time series for adequate statistical modeling of extreme rainfall.

## Future Rainfall

The following projected future rainfall data set was acquired for this purpose.

1. Projected future daily precipitation from the University of California (San Diego)'s Localized Constructed Analogs (LOCA) product, which employed statistical downscaling techniques to spatially downscale and bias-correct CMIP5 global climate model output.

A form of regional frequency analysis method was used in fitting consistent Depth-Duration-Frequency (DDF) curves to daily historical and downscaled-model Annual Maximum Series (AMS) data at daily stations in Miami-Dade County for durations of 1, 2, 3, 4, and 7 days. For stations with hourly historical AMS data available, DDF curves were additionally fit for durations of 1, 2, 3, 6, and 12 hours. The DDF curves were fit for two different sets of historical observations. The first set consisted of a total of 59 stations with sufficient AMS data available up to the year 2018 (33 hourly and 26 daily stations). This set was used to develop, compare, and recommend the updates to rainfall maps in the Florida Building Code. The second set of historical DDF curves was developed from 26 stations with sufficient AMS data available up to the year 2005 (14 hourly and 12 daily stations). This second set was used to bias-correct the LOCA statistically downscaled extreme precipitation products for the period 2050-2079. The 2005 cutoff in the second historical dataset was chosen to match the historical period in LOCA.

## Results

Figure 7 and Figure 8 show contour maps of hourly and daily 1-in-100 year rainfall totals based on thin plate spline (TPS) smoothing of the fitted DDF data at each station with sufficient AMS data available up to the year 2018. Fitted 1-in-100-year hourly rainfall totals range from 3.5 to 8.2 inches with most values below 6.5 inches with the exception of two outlier stations: S29-R and 08-4091. The generalized surface based on TPS ranges from 4.8 to 5.7 inches for the 1-in-100-year hourly rainfall events. Fitted 1-in-100-year daily rainfall totals range from 7.7 to 18.2 inches with most values below 15 inches with the exception of the same two outlier stations: S29-R and 08-4091. After generalizing the surface using TPS with a smoothing factor of 0.02, the fitted values range from 8.1 to 13.7 inches for the 1-in-100-year daily rainfall events. Maps corresponding to other durations are provided in Appendix II.

Frequency estimates of future rainfall were derived from LOCA climate data but with bias correction. Based on the estimates from the number of LOCA model datasets, changes in the extreme rainfall from current to future (2065) were determined. Sample tables are shown in Tables 2 and 3 for 1-hour and 1-day, respectively. Future one-hour, 100-year rainfall change ranges from about 13% to 44% with a median increase of about 7%. For 1-day duration, the range is from -14% to 45% with a median increase of about 6%. To estimate the future potential rainfall, we used the median increase to produce the maps shown in Figure 9 and Figure 10.

*Table 2. Changes in adjusted 1-hr DDF precipitation depths in inches (%) for various return periods for the future period centered at 2065 versus observations in the current baseline period. 5-95th percentiles across models shown.*

| Percentile. | 60-min_2-year | 60-min_5-year | 60-min_10-year | 60-min_25-year | 60-min_50-year | 60-min_100-year |
|---|---|---|---|---|---|---|
| 5% | -0.37 (-17.5%) | -0.37 (-12.8%) | -0.42 (-12.3%) | -0.47 (-11.4%) | -0.53 (-11.3%) | -0.75 (-13.3%) |
| 10% | -0.22 (-10.5%) | -0.32 (-11.3%) | -0.38 (-10.8%) | -0.37 (-8.8%) | -0.46 (-9.4%) | -0.58 (-11.1%) |
| 50% | 0 (0.1%) | 0.04 (1.5%) | 0.11 (3%) | 0.17 (3.5%) | 0.26 (5.4%) | 0.39 (7.1%) |
| 90% | 0.27 (12.8%) | 0.45 (15.5%) | 0.67 (19.8%) | 1.09 (25.9%) | 1.32 (27.8%) | 1.67 (30.9%) |
| 95% | 0.32 (14.8%) | 0.65 (22.6%) | 0.86 (25%) | 1.3 (31.1%) | 1.78 (37.5%) | 2.34 (43.8%) |

*Table 3. Changes in adjusted 24-hr DDF precipitation depths in inches (%) for various return periods for the future period centered at 2065 versus observations in the current baseline period. 5-95th percentiles across models shown.*

| Percentile. | 24-hr_2-year | 24-hr_5-year | 24-hr_10-year | 24-hr_25-year | 24-hr_50-year | 24-hr_100-year |
|---|---|---|---|---|---|---|
| 5% | -0.42 (-16.1%) | -0.45 (-12.6%) | -0.52 (-12.1%) | -0.57 (-11%) | -0.74 (-10.6%) | -1.04 (-14.5%) |
| 10% | -0.29 (-10.4%) | -0.37 (-10.5%) | -0.44 (-9.8%) | -0.5 (-8.7%) | -0.62 (-9.7%) | -0.83 (-10.1%) |
| 50% | -0.01 (0.2%) | 0.03 (1.6%) | 0.01 (1.8%) | 0.06 (2.5%) | 0.14 (3.9%) | 0.2 (5.7%) |
| 90% | 0.29 (11.8%) | 0.5 (15%) | 0.77 (19.9%) | 1.22 (25%) | 1.45 (27.2%) | 1.65 (29.3%) |
| 95% | 0.35 (13.6%) | 0.69 (19.6%) | 0.91 (21.9%) | 1.3 (28.3%) | 1.83 (36.6%) | 2.52 (44.7%) |

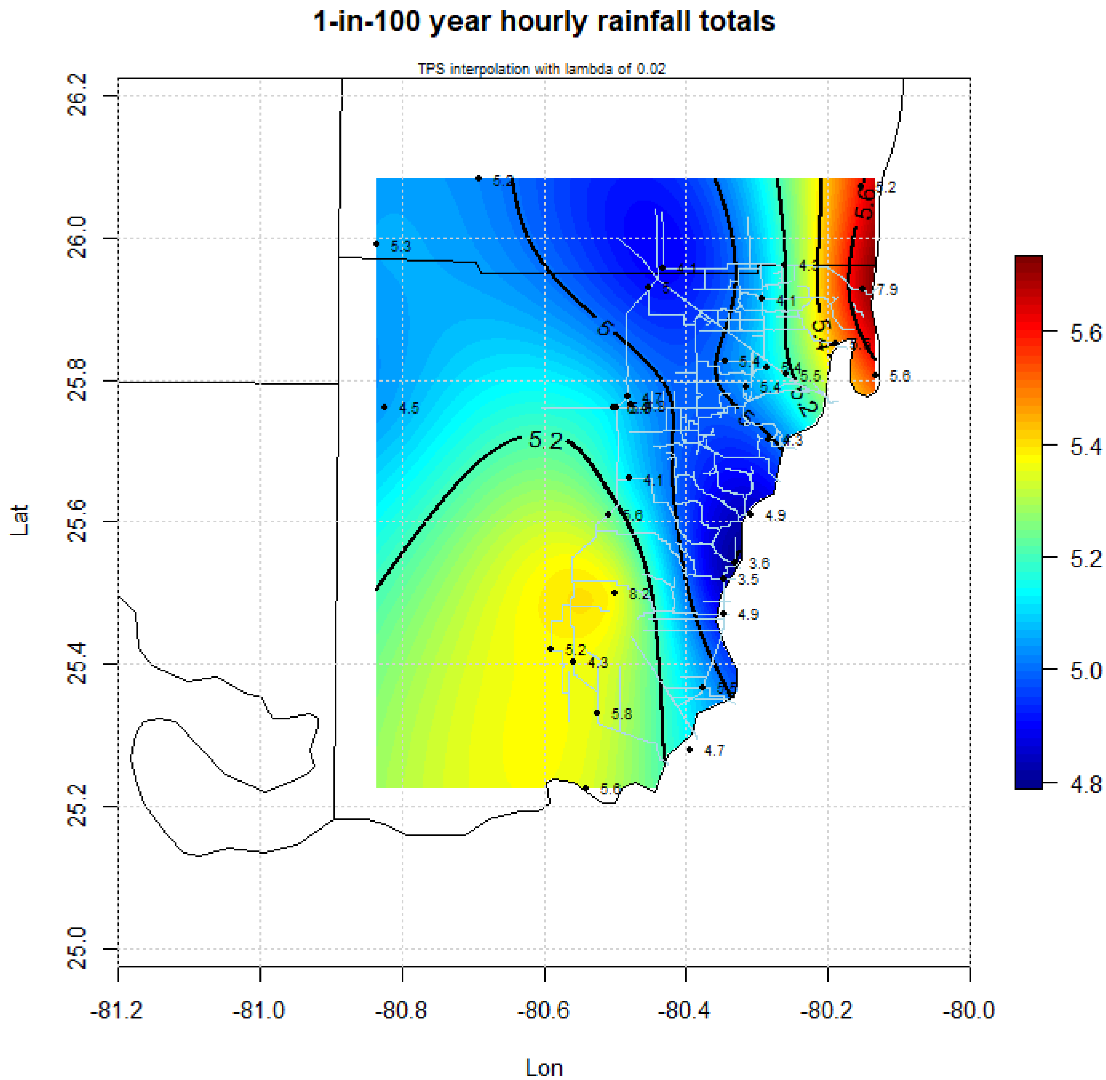


*Figure 7. 1-in-100-year hourly rainfall totals (inches) based on thin-plate-spline (TPS) smoothing of station data (in black).*

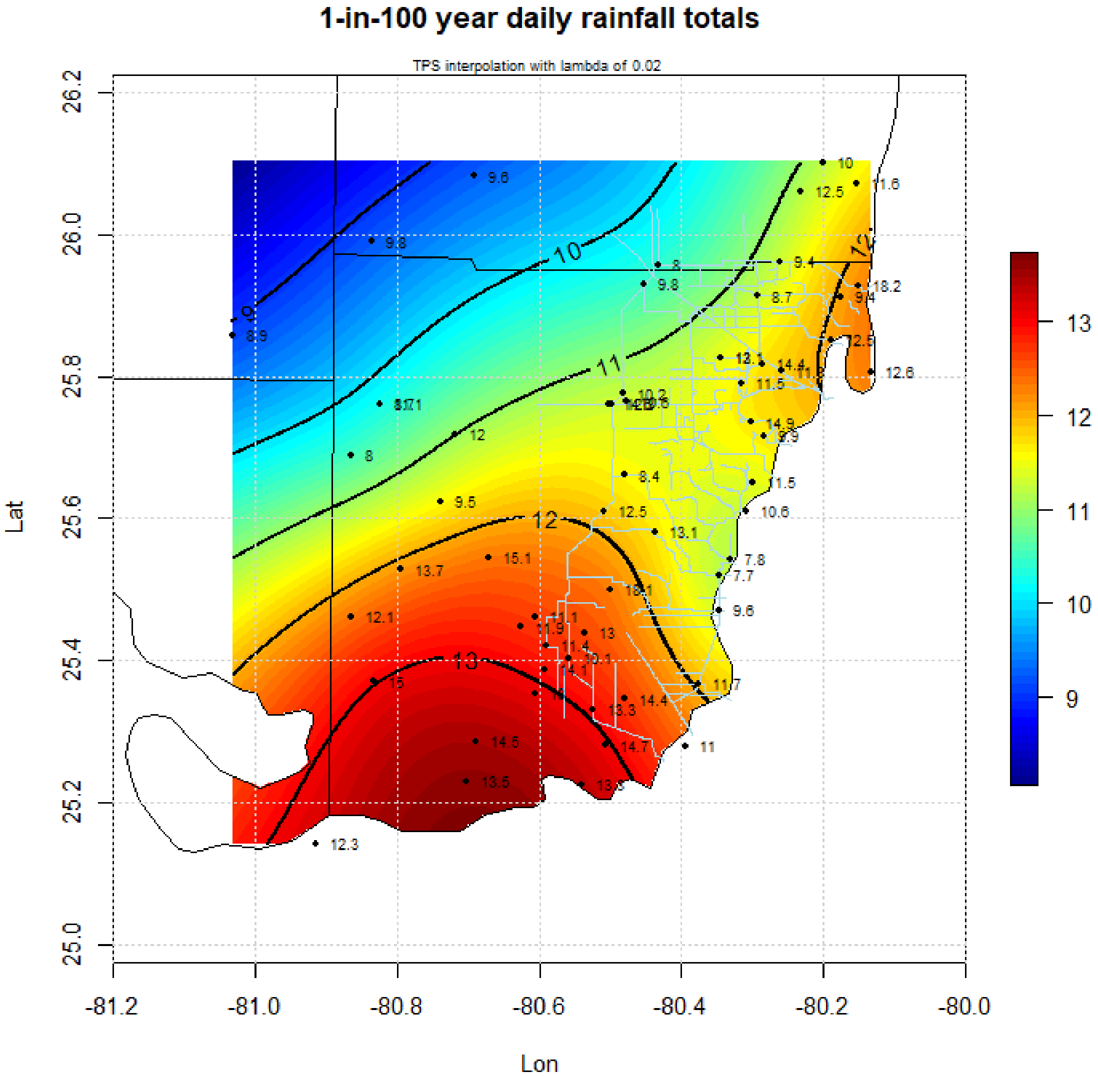


*Figure 8. 1-in-100-year 3-day rainfall totals (inches) based on thin-plate-spline (TPS) smoothing of station data (in black).*

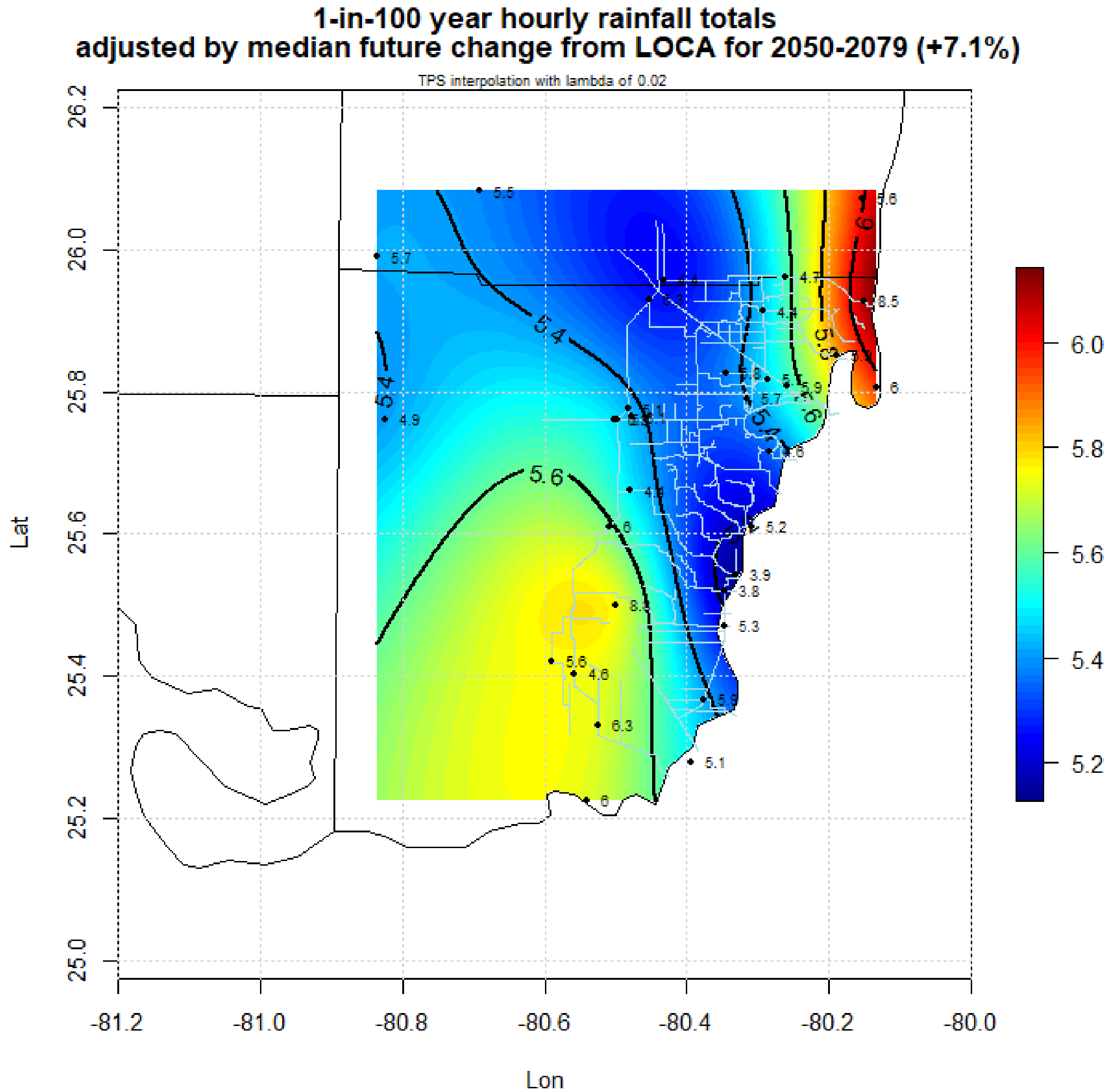


*Figure 9. Estimated future 1-hour, 100-year rainfall predicted using LOCA rainfall.*

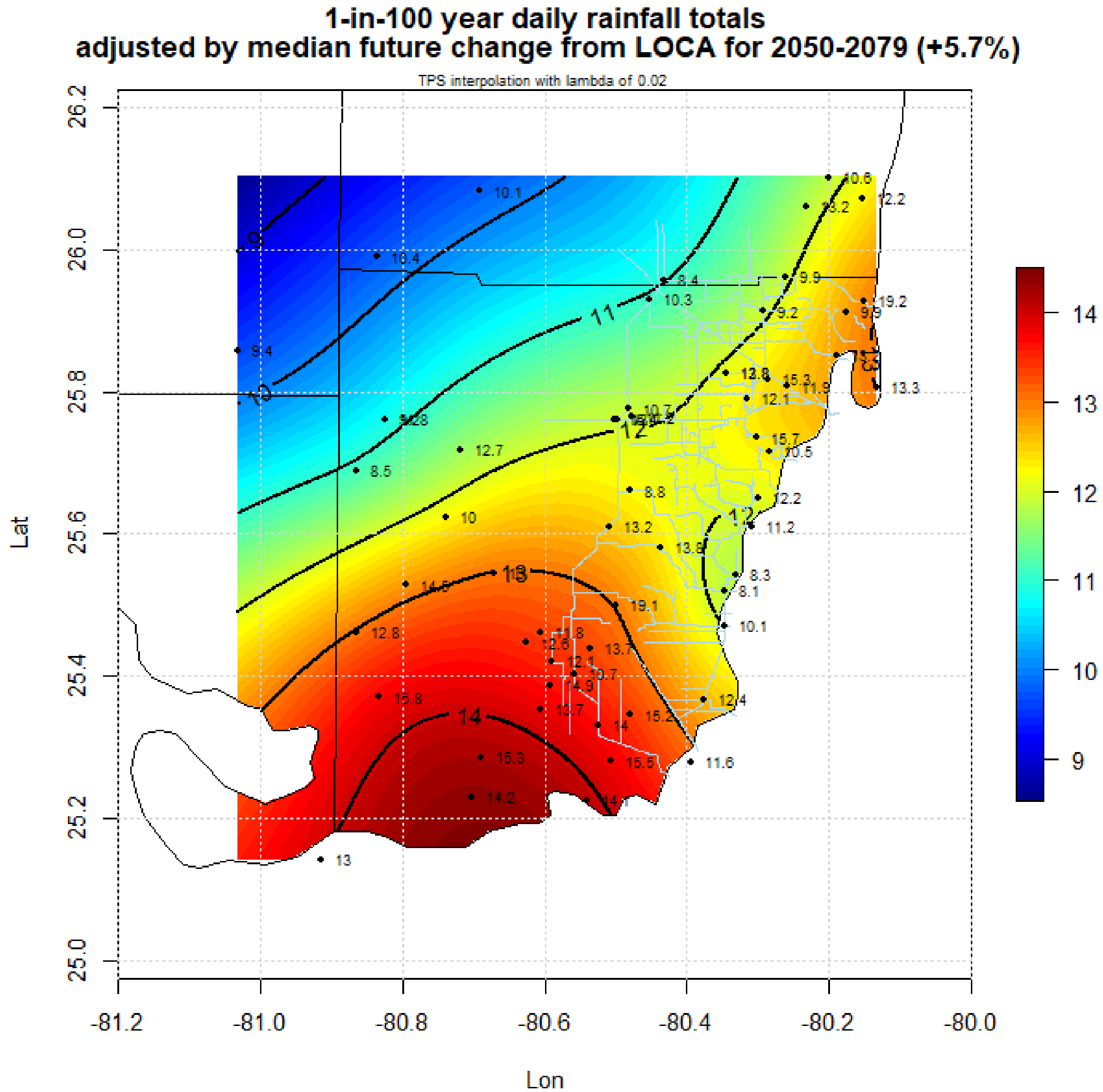


*Figure 10. Estimated future daily rainfall predicting using LOCA data.*

## Comparison with Existing Maps

The current FBC recommends the use of its Figure 1611.1 for rain loads (1 hour, 100-year). This map appears to have been reproduced from NOAA's Hydro-55 publication dating back to 1977. Several other agencies have developed maps of rainfall for various frequencies and they include NOAA (Atlas 14) and SFWMD. Only a NOAA Atlas 14 map is available for 1-hour, 100-year rainfall and it is shown in Figure 11. Comparison of this figure with Figure 7 produced for this project show that the 100-year, 1-hour rainfall estimates are quite similar although the spatial patterns are somewhat different. For daily rainfall, both SFWMD and NOAA (Atlas 14) have published maps. They are shown in Figures 12 and 13 respectively. When compared to the daily map for 100-year return period, SFWMD estimates are similar to those shown in Figure 8. NOAA Atlas 14 estimates appear to be higher than the daily, 100-year estimates produced for this study.

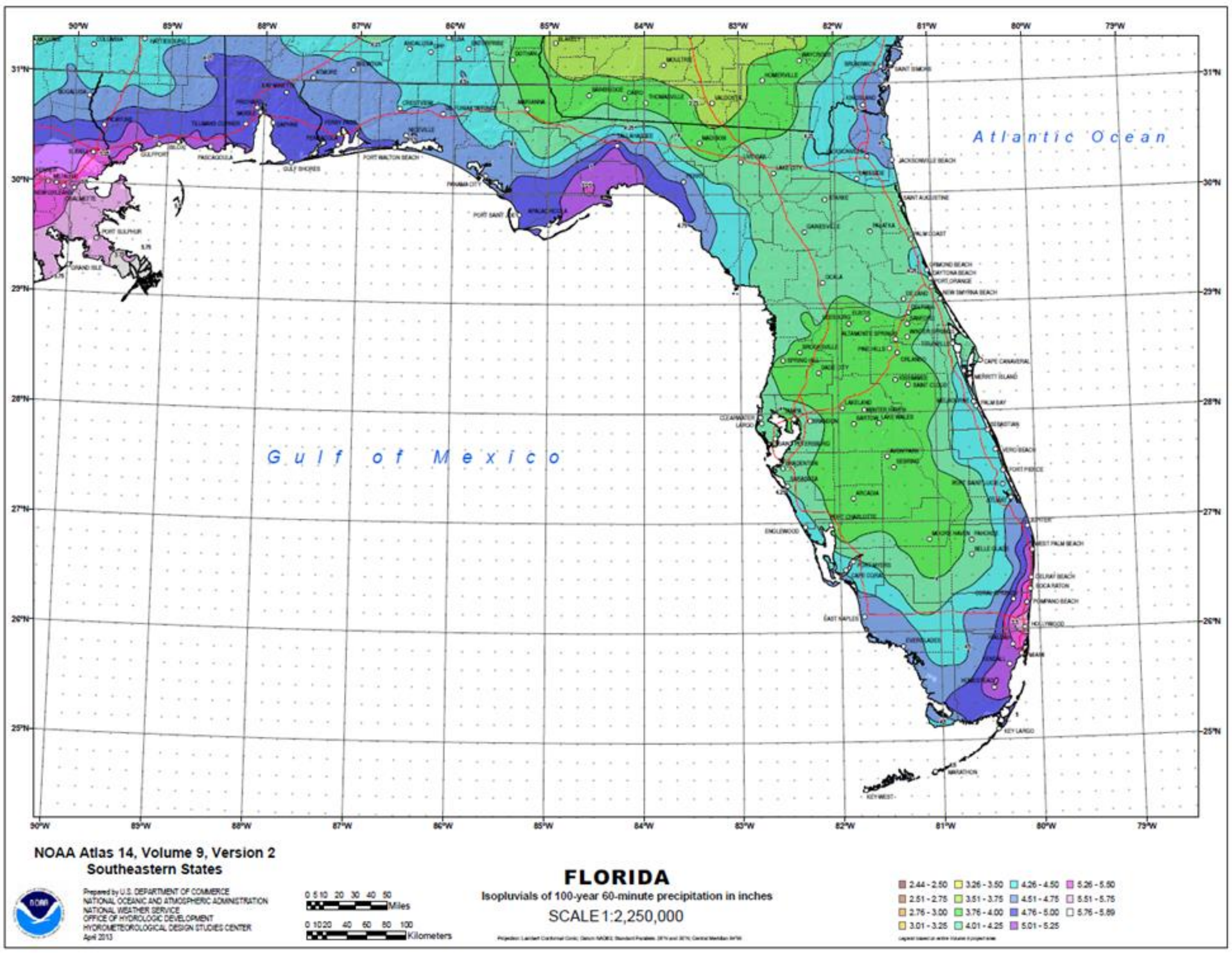

*Figure 11. NOAA Atlas 14 map for 1 hour, 100-year rainfall*

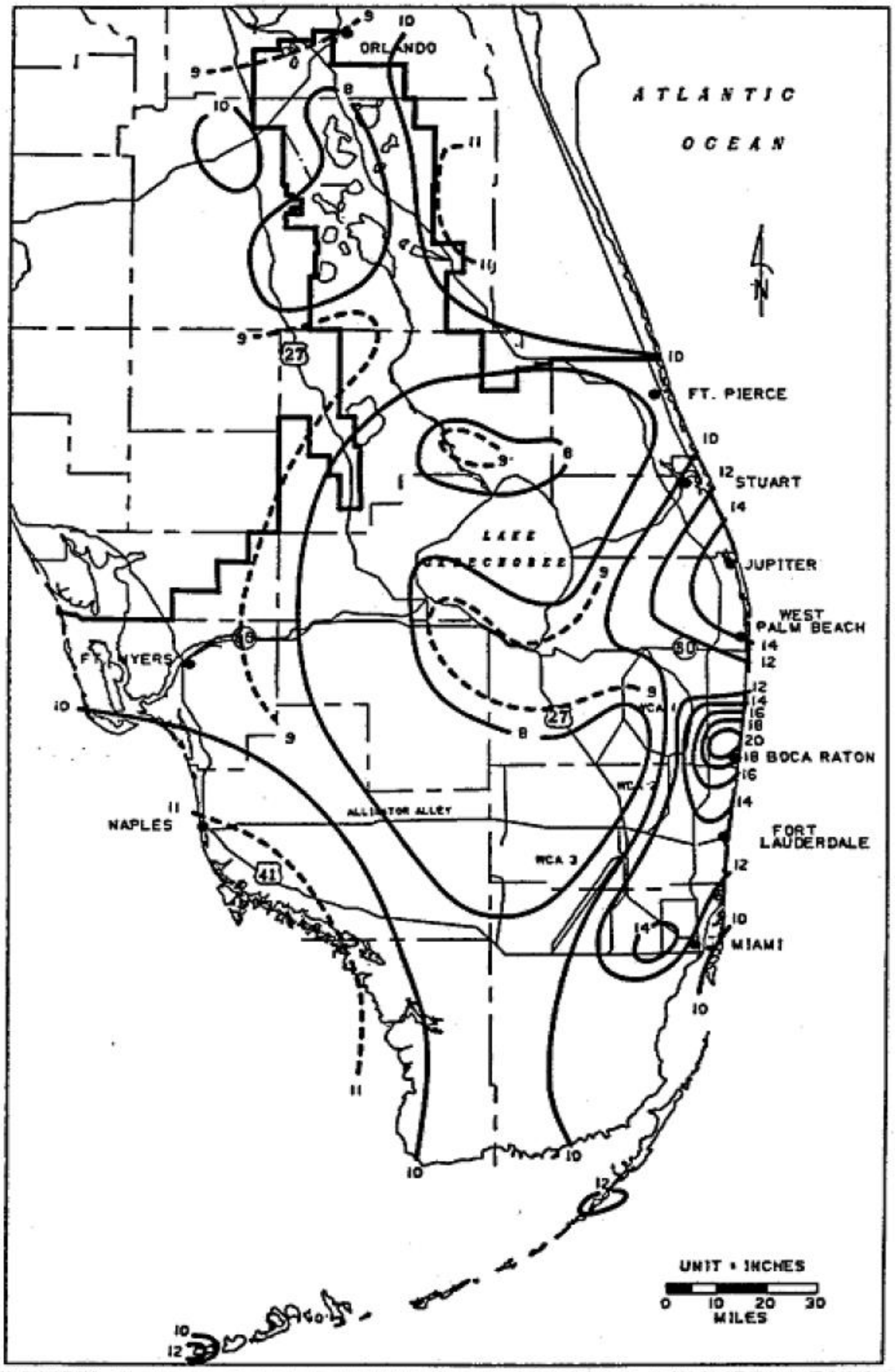


FIGURE C-6. 1-DAY RAINFALL: 100-YEAR RETURN PERIOD

*Figure 12. SFWMD maps for daily, 100-year rainfall*

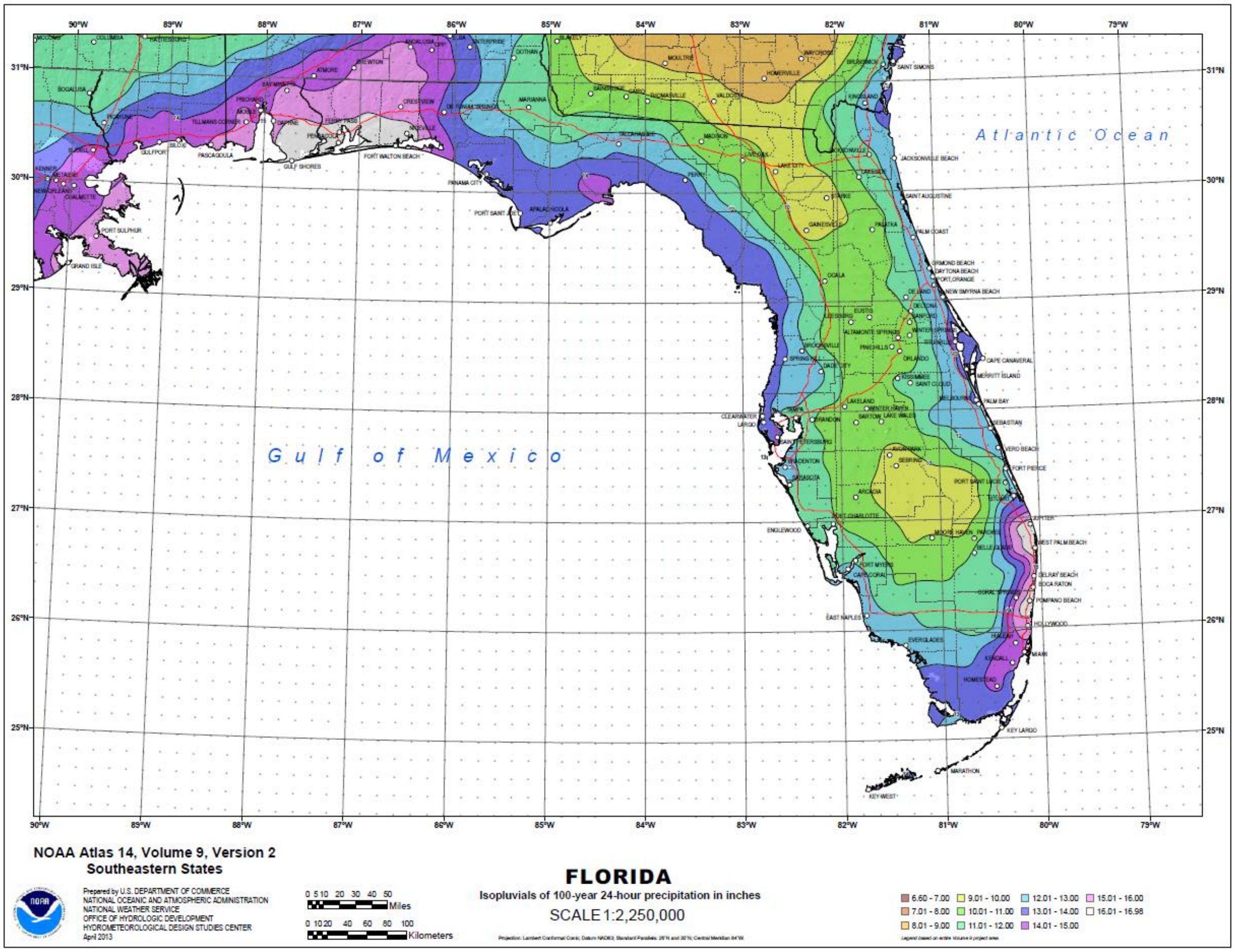

*Figure 13. NOAA Atlas 14 map for daily, 100-year rainfall*

## Discussion

As the best available data, we recommend that the current 100-year hourly rainfall map (Figure 1611.1) be replaced by Figure 9 above. The existing figure is quite dated (late 1970s) and the new analysis used the most recent extreme rainfall observations. Comparison of the new maps for the historical period show that our estimates are similar to what had been produced by NOAA (Atlas 14) although NOAA's daily values are somewhat higher. The other extreme rainfall estimates provided in the Appendix II may also be used for flood load computations.

## III. Evaluation of the FBC-related requirements

This task required the following subtasks:

- FIU SLSC shall evaluate the current Florida Building Code requirements to recommend what additional steps will be necessary to incorporate results of the proposed study into the sections of the Codes mentioned above. Specifically, the changes to the rain loads and their implications for rain loads as applied to figure 1611.1 and figure 1106.1 of the FBC, Plumbing, shall be recommended.

- FIU SLSC shall evaluate how the groundwater table maps and the revised rainfall maps should be used to update the flood loads as applied to Chapters 16 and 31 of the 6th Edition, Florida Building Code (2017), Building. The groundwater table maps and the revised rainfall maps shall also be reviewed to determine if an update to Chapter 3 of the 6th Edition, Florida Building Code (2017), Residential, is necessary.

- FIU SLSC shall provide specific recommendations for modifications to the Florida Building Code that are necessary to incorporate the updated information on groundwater elevation due to sea level rise and rainfall.

To evaluate potential implications of sea-level rise and changing rainfall in the Florida Building Code for communities in Florida using Miami-Dade County as a case study, we evaluated the current Florida Building Code requirements to recommend what additional steps will be necessary to incorporate results of the proposed study into the sections of the Codes mentioned above. Specifically, we evaluated 1) the changes to the rain loads and their implications for Rain Loads as applied to Figure 1611.1 and Figure 1106.1 of the FBC, Plumbing, 2) how the groundwater table maps and the revised rainfall maps should be used to update the Flood loads as applied to (Chapter 16), Flood Resistant Construction (Chapter 3, Section R322), and the structures seaward of the coastal construction line (Chapter 31, Section 3109) of the FBC, and 3) specific recommendations for Code modifications to incorporate the updated information on groundwater elevation due to sea level rise and rainfall. Individual sections have been reviewed and a set of preliminary considerations are being put forth from which, when evaluated along with new flood and rain data, recommendations were drawn. Preliminary considerations include defining a "coastal zone", similar to a "coastal A zone" for floodplain management, with implications for building, plumbing, and residential sections of the code. Detailed discussions for relevant section of the FBC are provided in Appendix III. Additional information, such as the projected saltwater intrusion front, is provided in Appendix I and may be used to support recommendations for code changes.

## Summary of Key Recommendations

**Objective 3.3:** Provide specific recommendations for Code modifications to incorporate the updated information on groundwater elevation due to sea level rise and rainfall.

Rain Loads

1. Recompute the flow capacities provided in Tables 1106.2 and 1106.3 with large roof areas using the new rain load data.

Flood Loads

1. It is recommended that the V-zone and coastal A-zones be used as a proxy to delimit the below grade areas where code could regulate the use of saltwater corrosion-resistant materials associated with foundations, and for anchorage of walls and columns to foundations, following guidance for aboveground structural components provided in ASCE 24. Geotechnical investigations can be used to verify presence and depth to saline groundwater.
2. To accommodate the analytical uncertainties and multiple sources of flooding not accounted for in the current effective FEMA FIRM, notably in the coastal A-zone, it is recommended that at least one foot be added to the ASCE 24 elevation requirements provided in Tables 2.1 and 4.1 and the higher water surface elevation used to delineate additional land area that would be inundated if the water rose to BFE plus 2 or 3 feet. This additional map showing a "future" flood hazard area could be used to apply floodplain requirements to development. It is recommended to add to bullet 1 of section 1603.1.7, after ASCE 24, "plus 1 foot, or the design flood elevation, whichever is higher, to account for continuing sea level rise, using data updated every 5 years." It is recommended to add to bullet 1 of section R322.3.2: "To account for SLR and recurring influence of astronomical tide (free water on surfaces), … is elevated to or above the base flood elevation plus 2 feet (610 mm), or the design flood elevation, whichever is higher, using data updated every 5 years." For clarity, these specific modifications to ASCE 24 could also be provided in section 1612.4.1.
3. Currently, the FBC Section 1804.5 does not allow fill in coastal high hazard areas and coastal A zones "unless the fill is conducted and/or placed to avoid diversion of water and waves toward any building or structure". It is recommended that the FBC be modified to fully treat Coastal A Zones (when Limit of Moderate Wave Action is delineated) as coastal high hazard areas (Zone V) under conditions where riverine flooding (floodway) intersects Coastal A zones and/or V zones. In Coastal A Zones (seaward of Limit of Moderate Wave Action), ASCE 24 Sec. 4.3.15 and R322.3.3 allow stem wall foundations backfilled to the underside of the

floor system provided the foundations are designed to account for wave action, etc. A Florida-specific provision in Sec. 1612.4.1 modifies ASCE 24 to permit dry floodproofing (nonresidential only) in Coastal A Zones if wave loads, erosion and local scour are accounted for in the design. Following 1612.3.2, it is recommended that the intersection of riverine and flooding to BFE in the Coastal A zone (or inland of the V zone) be considered as part of floodway analysis so that the "cumulative effect of encroachment into a floodway, when combined with all other existing and anticipated flood hazard area encroachment, does not increase the design flood elevation more than 1ft at any point" as a result of allowing stem wall foundations backfilled to the underside of the floor (*cf*. 1612.3.2 and 1804.5) under these conditions.

4. It is recommended that the FBC provide the standardized approaches or make reference to the standard approaches it recommends for use for groundwater control (Section 1805.4).
5. To ensure the most up-to-date sea-level rise projections are being taken into consideration to evaluate future flooding condition associated with continued sea-level rise and design of flood elevations, it is recommended that there be a harmonized procedure for developing a unified projection for each region of the State, that is updated every 5 years and mandated for use in the FBC.
6. Mandate use of depth to groundwater maps, updated every 5 years, to specify where installation of septic tanks should be prohibited (*cf.* R322.1.7), to comply with Section 101.3. where FBC provides for "minimum requirements for reasonable safety, public health and general welfare". Coordinate with FDEP and FDOH.
7. ASCE 24 is not referenced consistently across the volumes. Some sections specifically reference guidance presented in ASCE 24, whereas other sections do not.
   a. It is recommended that ASCE 24 be referenced consistently to help clearly and efficiently guide the user to the in the way the FBC intends.
   b. It is also recommended to add in the following statement: The design and construction of buildings and structures located in flood hazard areas, including coastal high hazard areas and Coastal A Zones, "and those flood-resistant provisions of the FBC cross-referenced in Table 1612.1," shall be in accordance with Chapter 5 of ASCE 7 and with ASCE 24.
   c. It is recommended to reference ASCE 24 in the following text of section 1604.5. 2.. than the occupancy category specified therein "(e.g., "Flood Design Class in ASCE 24)."
8. It is recommended to add to list of elements in section 1803.6: 1) date of last geotechnical investigation, 2) if water table is not encountered, location of nearest well and water table depth at time of geotechnical investigation, to a cross-referenced benchmark, 3) whether

the fill materials may be exposed to shrinking/swelling, and included in special design and construction provisions, 4) in foundation recommendations, type and design considerations for shrinking/swelling and salinity, and 5) document municipal regulations on setback and clearance and alternate design criteria recommendations.

9. With regard to provisions for Special Detailed Requirements Based on Use and Occupancy, it is recommended that the following text be added in 453.2:
    a. "Exception: Educational facilities in flood hazard areas must comply with this code or the floodplain management ordinance of the municipality having jurisdiction."
    b. After "Section 1013.38, *Florida Statutes*.": "Consistent with 105.14, permit issued on basis of a sworn affidavit shall not extend to flood load and flood resistance requirements of the Florida Building Code."
10. It is recommended to add definitions missing from Section 202 for clarity: "return period" and "combined total storm tide elevation".
11. It is recommended that, like section R322.1.8, new, relevant FEMA publications on flood-resistant materials be referenced throughout.

## Summary of Priority Research Areas

### Rain Loads

1. Determine the rainfall rate maps for different return intervals, at least 15-min, 100-yr, and compare with 1-hr, 100-yr for the State, for both historical and recent.

### Flood Loads

1. Determine and apply a method to provide a scientific-basis for design flood elevations, based on uncertainties in flood frequency analyses, hydraulic modeling, increasing sea level, expected watershed development, changing rainfall patterns, and sources of flooding unaccounted for by FEMA BFE (e.g., sea level rise).
2. Evaluate whether and under what conditions the coastal A-zone and V zone designations are appropriate as a proxy to delimit the below grade areas where code should regulate the use of saltwater corrosion-resistant materials associated with foundations, and for anchorage of walls and columns to foundations. Reevaluate and update every 5 years.
3. Develop test cases for "future" flood hazard area maps that could be used to apply floodplain requirements to development by adding 1 foot to the ASCE 24 elevation requirements provided in Tables 2.1 and 4.1 and then use that higher water surface elevation to delineate additional land area that would be inundated if the water rose to BFE plus 2 or 3 feet. Reevaluate and update every 5 years.
4. Advancements in experimental facilities and modeling warrant review, and possible update, of load combinations that include flood and the recommended flood load

factor applied in V- and coastal-A zones. The flood load factor provided in ASCE 7 for computing load combinations has not been updated since prior to 2005 (see commentary on p.256, C2.3.3. in ASCE 7-05 for a discussion of determination of flood load criteria).

5. New research may be needed to compute and evaluate the cumulative flood hazard area encroachment via fill when riverine floodways intersect with Coastal A zones/V zones or areas inland of V zones using different storm tide elevations or BFE +2 or +3 feet, depending on occupancy, as the coastal boundary condition (*cf*. 1612.3.2 and 1804.5). Dry floodproofing under these conditions may also warrant evaluation of cumulative flood hazard area encroachment.
6. Given the critical nature of Flood Design Class 4 structures, it is recommended that a study be conducted on the cost-benefit of reducing the substantial improvement/damage percentage criteria (<50%).
7. For the combined total storm tide elevations determined by FDEP for use with the coastal construction control line (CCCL), although FEMA has updated modeling that in many areas has brought BFE closer to the combined total storm tide elevations determined by FDEP, we do not know to what extent the uncertainties in analyses and modeling and sources of flooding compare with combined total storm tide elevations (*cf*. Section 3109). It is recommended that the work continue to evaluate: a) how the combined total storm tide elevation for the 100-yr return period be evaluated against those using other, approved methods of determining that value, and b) the 500-yr combined total storm tide elevation for consideration and use for Flood Design Class 4 structures (compared with BFE, DFE and cost-benefit). Where the CCCL does not align with V zones, we also recommend an assessment of how increasing the inland extent of the CCCL to include V- zones reduces potential structural damage. Based on the results of these studies, further code or legislative changes pertaining to CCCL may be warranted.

## References

Bakker, M., Schaars, F., Hughes, J.D., Langevin, C.D., and Dausman, A.M., 2013, Documentation of the seawater intrusion (SWI2) package for MODFLOW: U.S. Geological Survey Techniques and Methods, book 6, chap. A46, 47 p., https://pubs.usgs.gov/tm/6a46/.

Frederick, R.H., V. A. Myers, E. P. Auciello (1977). NOAA Technical Memorandum NWS Hydro-35, Five- to 60-Minute Precipitation Frequency for the Eastern and Central United States, National Weather Service, Silver Spring, MD.

Hughes, J.D., Langevin, C.D., Chartier, K.L., and White, J.T., 2012, Documentation of the Surface-Water Routing (SWR1) Process for modeling surface-water flow with the U.S. Geological Survey

Modular Ground-Water Model (MODFLOW–2005): U.S. Geological Survey Techniques and Methods, book 6, chap. A40 (Version 1.0), 113 p. https://doi.org/10.3133/tm6A40.

Hughes, J.D., and White, J.T., 2016, Hydrologic conditions in urban Miami-Dade County, Florida, and the effect of groundwater pumpage and increased sea level on canal leakage and regional groundwater flow (ver. 1.2, July 2016): U.S. Geological Survey Scientific Investigations Report 2014–5162, 175 p., http://dx.doi.org/10.3133/sir20145162.

Tetratech. 2015. Hydrologic Design Standards under Future Climate for Grand Rapids, Michigan. Prepared by Tetratech for the City of Grand Rapids, Michigan.

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