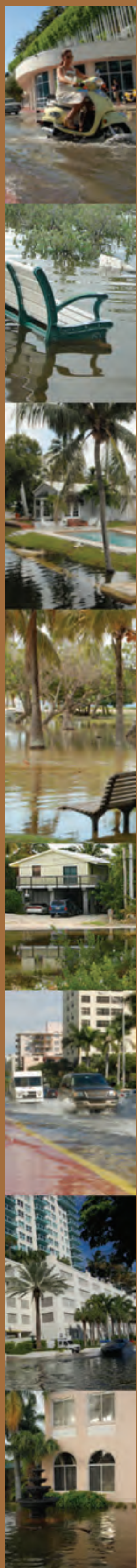
Appendix B - Southeast Florida Climate Change Compact -Regional Inundation Mapping Methodology



Regional Methods for Mapping Sea Level Rise Inundation Vulnerability in Southeast Florida

Prepared By:

Diana Umpierre, GISP
Senior Geographer
South Florida Water Management District (SFWMD)

In Coordination With:

Southeast Florida Regional Climate Change Compact Inundation Mapping & Vulnerability Assessment Work Group

With Significant Support From:

NOAA's National Ocean Service (NOS), in particular Coastal Services Center and CO-OPS

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B-A. Metadata for NOAA's MHHW Tidal Surface for South Florida, in NAVD88 feet, Version 1
B-B. Example Geoprocessing Log for SLR Inundation Vulnerability Grid Layers

Cover Photos: *Coastal flooding photos were taken during higher than average high tide events. Numbered from top: Photos 1, 4, 6 and 7 were taken October 2010 by Miami-Dade DERM; photos 2 and 5 were taken September 2009 by The Nature Conservancy and Florida Keys GLEE; and photos 3 and 8 were taken October 2010 by Paul Krashefski (Broward Co Parks & Recreation).*

1.0 INTRODUCTION

This report describes the elevation-related datasets and mapping methods used by the Southeast Florida Regional Climate Change Compact ("*Compact*") Counties and the South Florida Water Management District (SFWMD) to develop regional sea level rise (SLR) inundation vulnerability surfaces. These were generated for 1, 2 and 3-ft SLR scenarios and used by each of the Compact Counties to estimate their specific vulnerability to SLR inundation and to provide valuable information on what concerns to address in the Compact's Regional Climate Change Action Plan.

Mapping the regional vulnerability to SLR inundation helps in identifying areas at potential risk and in planning for climate-resilient communities. In early 2010, the Compact Steering Committee formed an ad-hoc working group to develop and implement regionally consistent methods for mapping and analyzing regional SLR inundation vulnerability. This group, referred to as the *Inundation Mapping and Vulnerability Assessment Work Group* ("Work Group"), was composed of experienced Geographic Information System (GIS) practitioners and scientists representing the Compact Counties and the SFWMD, as well as local universities, non-profit organizations and other government agencies. They were assisted by experts from NOAA's Coastal Services Center (CSC) and Center for Operational Oceanographic Products and Services (CO-OPS) who provided key guidance, recommendations and assistance during development of regionally-consistent datasets and approaches for mapping SLR vulnerability and associated uncertainty.

The following sections describe the datasets and methods used to generate the estimated regional SLR inundation vulnerability surfaces. Among others, they include a discussion of the following key components:

- topographic digital elevation models (DEMs) using the 2007-08 LiDAR data from the Florida Division of Emergency Management (FDEM)
- NOAA's VDatum transformation grids and the initial Mean Higher High Water (MHHW) tidal surface extrapolated inland by CSC
- SLR vulnerability probability surfaces developed from Z-scores and documented elevation uncertainty

2.0 DIGITAL ELEVATION MODELS (DEMs)

2.1 Source Data Description

A key component to inundation mapping is the selection of topographic data sources to develop terrain digital elevation models (DEMs). The Compact inventoried available sources and evaluated their suitability for regional analysis. Important factors in their evaluation included: documented specifications, accuracy/ quality, regional availability and flight dates. After this review, the Compact agreed that the best available topographic sources were the following:

- 2007-08 Florida Division of Emergency Management (FDEM) LiDAR data
- USGS High Accuracy Elevation Dataset (HAED)

FDEM LiDAR

The FDEM LiDAR dataset covered most of the coastal urban SE Florida region and was selected by the Compact for their regional SLR vulnerability analysis. The data was collected via airborne LiDAR, which is a remote sensing technique that uses light pulses emitted from aircraft to measure elevations on the land surface. It produces densely-spaced elevation points (point clouds) that can cover large geographic areas relative quickly and with reasonable good accuracies. (Schmid K, et. al. 2008). The following are key characteristics and specifications of the FDEM LiDAR data collected in the SE FL region. (FDEM 2007).

- Specifications were the same for all areas flown and intended to support storm surge inundation modeling associated with hurricane evacuation planning.
- LiDAR flights were conducted between 2007 and 2008.
- Maximum point spacing in unobscured areas: 4 feet.
- LiDAR bare earth point clouds were delivered in a statewide tiling system of 5000-ft by 5000-ft tiles.
- Breaklines were extracted from LiDAR to improve hydro-enforcement.
- The coordinate system in SE FL was Florida State Plane, East Zone, NAVD 88, feet (GEOID03).
- Accuracy specifications were based on FEMA guidelines and tested with independent survey points.
  Horizontal: <= 3.8 ft at 95% confidence level
  Vertical: For open terrain (bare earth): <= .60 ft at 95% confidence level (RMSEz <= .30 ft)
  For other land covers: <= 1.19 ft at 95% confidence level (RMSEz <= .61 ft)
- An independent vendor conducted Quality Assurance (QA) review of vendor deliverables.

Figure 1 depicts the overall FDEM project extent in South Florida, as well as the specific delivery blocks for which SFWMD generated SLR inundation vulnerability data layers.

- Palm Beach East (Block 7)
- Broward (Block 6)
- Miami-Dade (Blocks 3, 4 and 5)
- Florida Keys (Blocks 1 and 2)
- Inland Monroe (Blocks 9 and 10) – *Not Used by the Compact Counties*

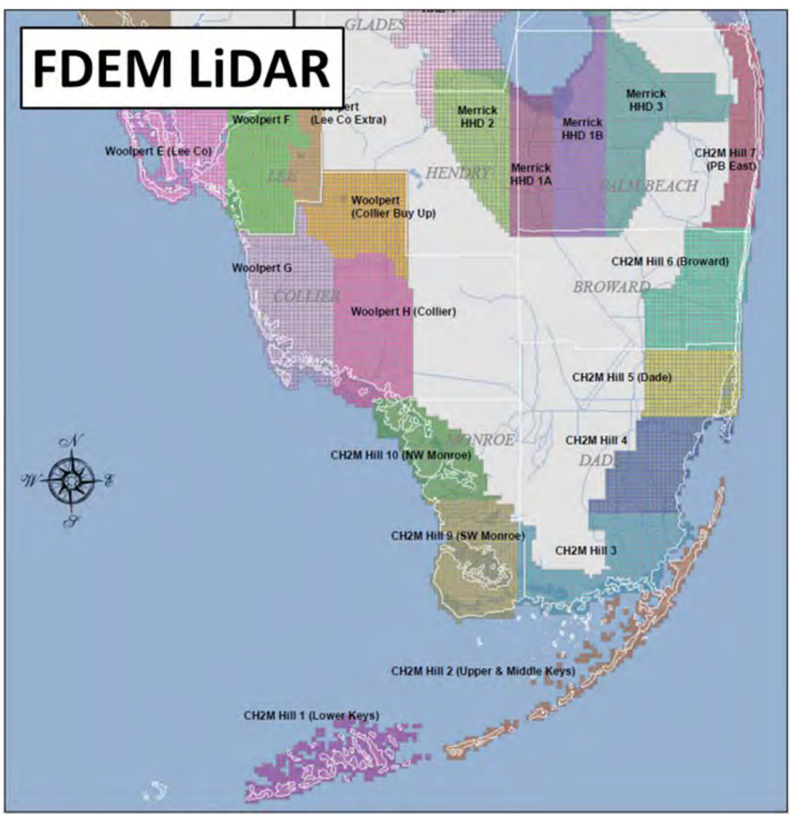


Figure 1 – Geographic Extent of the 2007-08 FDEM LiDAR Dataset within South Florida.

USGS HAED

The USGS HAED dataset was collected between 1995 and 2007 to support Everglades restoration efforts. The majority of the readings were collected from helicopters using an Airborne Height Finder (AHF), which is specialized equipment that drops a plumb-bob and uses a GPS to capture location coordinates and vertical elevation data. A smaller set of readings were collected by deploying surveyors on airboats. Readings were generally taken every 400 meters (~ 1312 ft). Unlike LiDAR, the USGS AHF system was reported as physically able to penetrate the heavy vegetation and murky waters that are common in the Everglades. USGS stated that the AHF system met their 15 cm (~ 0.5 ft) vertical accuracy specification, based on readings at several NGS 1st-order benchmarks. (Jones & Price 2007; USGS 2003). Vertical accuracy was not reported by land cover type.

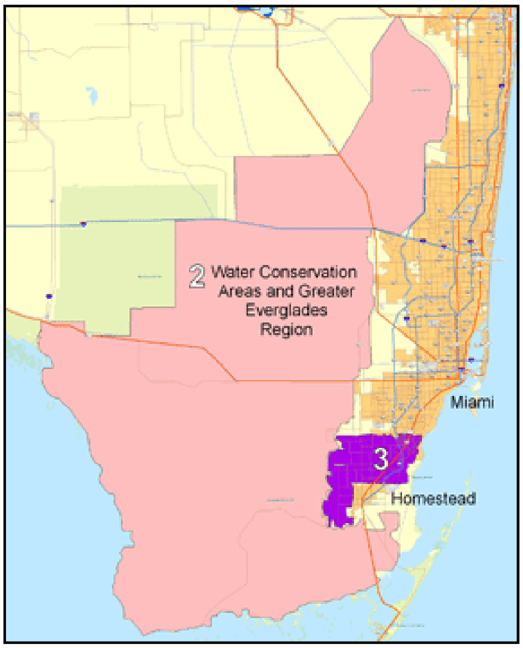


Figure 2 – Geographic Extent of USGS HAED
(Map Credit: USGS, retrieved from http://sofia.usgs.gov/exchange/desmond/desmondelev.html)

Although the USGS HAED was deemed the best available elevation data for the Everglades region, it was not possible to merge this dataset with the FDEM LiDAR dataset due to time and resource constraints. SFWMD did conduct a preliminary comparison of the USGS HAED and the FDEM LiDAR elevation data where these overlapped within inland Monroe to determine the feasibility of developing a merged DEM for all of South Florida. The assessment revealed that although the LiDAR data was commonly higher than the USGS data, the pattern was not consistent. Without field verification, the elevation differences would be too complex to resolve and to determine the proper adjustment methodology and the resulting vertical accuracy of such merged dataset. In addition to this issue, the Compact expressed concern that because the spacing of the readings was large (~ 1312 ft), certain features important to SLR impact analysis would be absent (e.g. canals, levees and elevated land associated with roads).

2.2 DEM Processing

SFWMD generated DEMs from the FDEM LiDAR data at various cell size resolutions. The Compact selected the 50-ft DEMs for their SLR vulnerability assessment. This section describes the processing steps and characteristics of the output DEMs.

SFWMD's DEM processing steps included creating Triangular Irregular Networks (TINs) from bare earth masspoints and breaklines. Five (5)-ft and 10-ft cell size DEMs were generated directly from the TINs using natural neighbor interpolation. Natural neighbor is an interpolation method available in ESRI's ArcGIS tools to develop DEMs from LiDAR data. It was also reported as the method selected by other agencies that have independently generated their own DEMs from the FDEM LiDAR data, specifically Broward and Miami-Dade counties, the United States Army Corps of Engineers (USACE) and Jones Edmunds, an FDEM consultant (Gassman, August 2010). Larger cell size DEMs (25, 50 and 100-ft) were generated from the mean of input 5-ft cells. The following were the main steps automated by SFWMD with custom ArcGIS python scripts and ArcCatalog commands.

- Process each project tile with a 500-ft buffer
  - Produce a TIN /Terrain using bare earth masspoints (LAS class 2) and breaklines (as noted in Table 1)
  - Generate 5-ft and 10-ft DEM rasters for each tile using Natural Neighbor interpolation
  - Run custom adjustment scripts, if needed (e.g. to flatten water bodies or fill tile corner voids)
- Combine tile DEMs (5-ft, 10-ft) into larger, typically county-size, DEMs
- Generate 25, 50 and 100-ft rasters using the mean of 5-ft input cells

Table 1 - Breaklines Types during TIN/Terrain Generation

Feature Class	Type
Masspoints (LAS Class2)	Masspoint
HydrographicFeature	HardLine
Roadbreakline	HardLine
Island	HardLine
SoftFeature	SoftLine
Waterbody	HardReplace
CoastalShoreline	HardErase

SFWMD processing also included a DEM Quality Assurance (QA) review. The primary objective of the DEM QA review was to identify and fix DEM artifacts introduced during processing (i.e. those *not* inherited from the source vendor data). The secondary objective was to get a general sense of qualitative characteristics of the data and communicate these to DEM users via the metadata. More detailed processing and QA information can be found in the DEM published metadata, accessible at SFWMD's GIS Data Catalog website (http://www.sfwmd.gov/gis, using keywords: FDEM LiDAR).

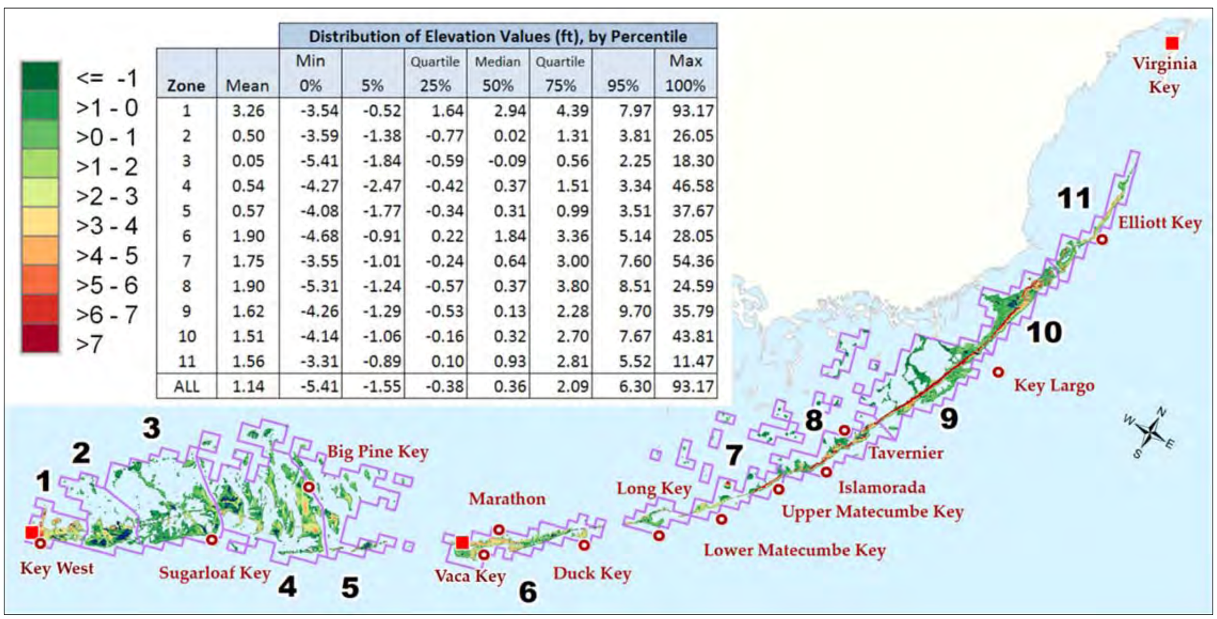
SFWMD's DEMs were also reviewed by NOAA CSC and USGS. NOAA has used these DEMs to help in the development of their web-based SLR viewer (http://www.csc.noaa.gov/slr). USGS has integrated them into the USGS National Elevation Dataset (http://ned.usgs.gov).

As with any elevation data collected via remote sensing technologies, the DEMs generated from the FDEM LiDAR data still have some artifacts that cannot be removed without considerable effort and expense. In fact, federal guidelines agree that it is *not* cost effective to attempt collecting LiDAR data that is 100% free and clean of artifacts. (FEMA, April 2003, p. A-42; NDEP, May 2004, p. 39-40)

Remaining artifacts often include a small number of buildings and some tree canopy. The collection of LiDAR data within inland coastal Monroe County and non-urban areas of southern and western Miami-Dade was particularly challenging because of the extent of mangrove forest and wetlands in those regions. Elevations on mangrove areas could be biased high because they may represent the top of mangrove roots and not the ground surface below the water and the thick, entangled network of mangrove roots that LiDAR light beams cannot easily penetrate. DEMs may also exhibit some banding that commonly aligns with flight paths. Some areas in the DEM could benefit from additional hydro-conditioning and hydro-enforcement to improve surface water flow patterns and hydrologic connections. Because Florida's topography is generally relatively flat, small errors in elevation values are challenging to address without considerable revision and field verification of breakline values.

Despite these known issues, the FDEM LiDAR data is by far one of the best documented regional topographic datasets in urban coastal Florida and was collected using comprehensive baseline specifications. For these reasons, the Compact counties considered it the best available topographic dataset for coastal SE Florida and was utilized it to conduct their SLR vulnerability assessments.

For illustrative purposes, the figures below are included to demonstrate the distribution elevation values in South Florida, based on the SFWMD DEMs that were generated from the FDEM LiDAR data. All elevations are in feet (NAVD88).



		Distribution of Elevation Values (ft), by Percentile						
		Min		Quartile	Median	Quartile		Max
Zone	Mean	0%	5%	25%	50%	75%	95%	100%
1	3.26	-3.54	-0.52	1.64	2.94	4.39	7.97	93.17
2	0.50	-3.59	-1.38	-0.77	0.02	1.31	3.81	26.05
3	0.05	-5.41	-1.84	-0.59	-0.09	0.56	2.25	18.30
4	0.54	-4.27	-2.47	-0.42	0.37	1.51	3.34	46.58
5	0.57	-4.08	-1.77	-0.34	0.31	0.99	3.51	37.67
6	1.90	-4.68	-0.91	0.22	1.84	3.36	5.14	28.05
7	1.75	-3.55	-1.01	-0.24	0.64	3.00	7.60	54.36
8	1.90	-5.31	-1.24	-0.57	0.37	3.80	8.51	24.59
9	1.62	-4.26	-1.29	-0.53	0.13	2.28	9.70	35.79
10	1.51	-4.14	-1.06	-0.16	0.32	2.70	7.67	43.81
11	1.56	-3.31	-0.89	0.10	0.93	2.81	5.52	11.47
ALL	1.14	-5.41	-1.55	-0.38	0.36	2.09	6.30	93.17

Figure 3 - Elevation Distribution in the Florida Keys (NAVD88, ft)
The distribution of elevation values was generated using the 25-ft DEM generated from the FDEM LiDAR data. Calculated data is courtesy of Tim Liebermann (SFWMD).

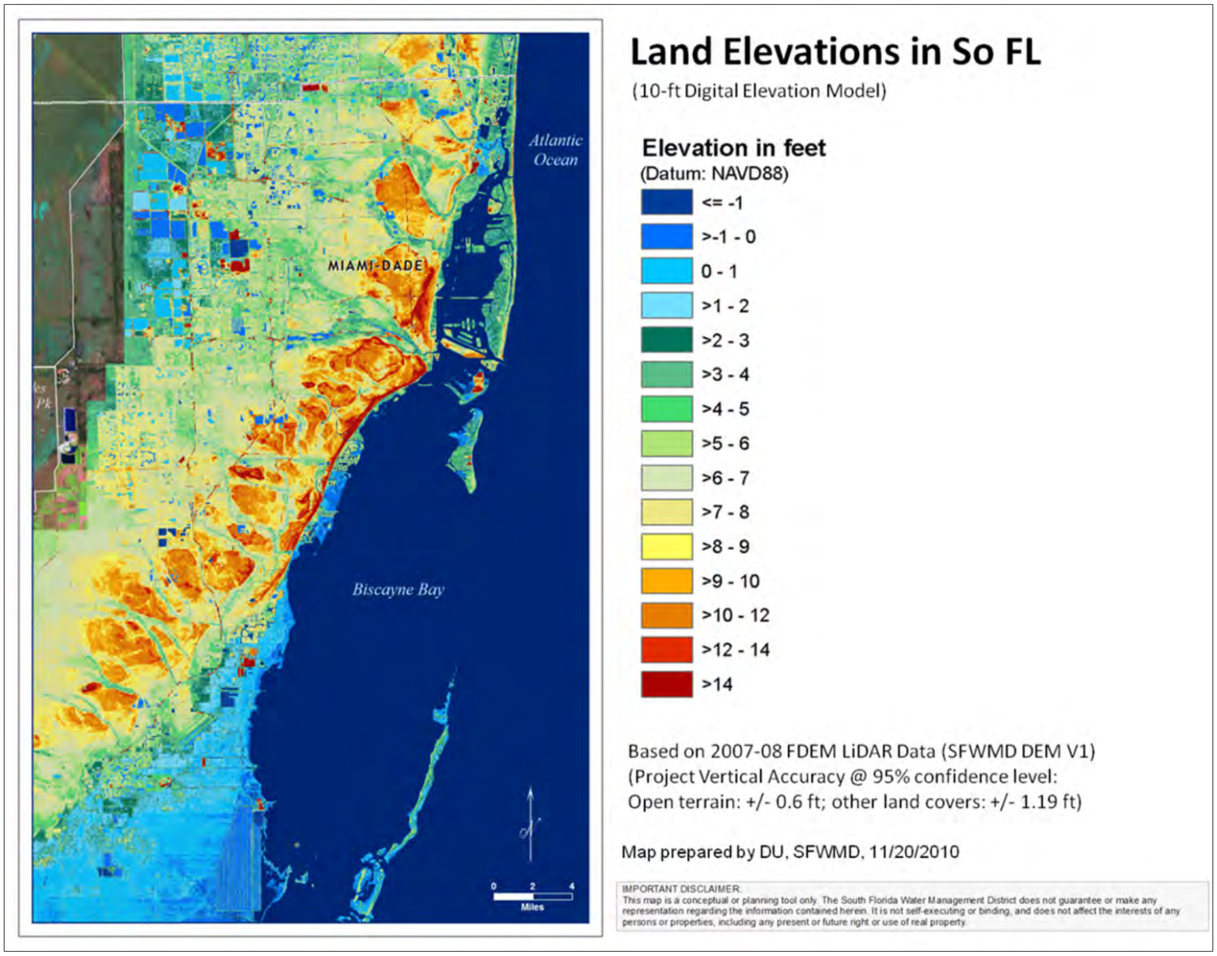


Figure 4 – Land Elevations along Urban Coastal Miami-Dade (NAVD88, ft)
Elevation values were classified in value ranges which were color-coded to help illustrate the general elevation distribution. The map was created using the 10-ft DEM generated by SFWMD from the FDEM LiDAR data.

3.0 SLR Modified Bathtub Approach

Regional SLR inundation vulnerability was mapped by using a modified bathtub method recommended by NOAA CSC and agreed-to by the Compact. The bathtub approach basically entails flooding the land with a water surface that accounts for rising seas. The bathtub effect is simulated by intersecting the land surface with a water surface that includes the added water of a given SLR scenario linearly superimposed over the baseline reference (0-ft SLR) tidal water surface. Both surfaces are referenced to a common vertical datum. The traditional version of the bathtub method applies a flat, single-value water surface to the variable land surface. However, applying a single-value regional water surface across all of SE Florida was not deemed an appropriate approach by either NOAA or the Compact. Water level readings at NOAA stations along the SE Florida coast reveal considerable regional elevation differences. Therefore, a “modified” bathtub approach was implemented based on recommendations by NOAA CSC experts. The modified approach entailed using a modeled, varying water tidal surface that takes into account the observed tidal datum variability in South Florida. This approach has also been used by NOAA CSC for the data displayed in their web-based SLR map viewer. (Marcy et.al. June 2011; NOAA CSC August 2010b). Additional details about the modeled tidal surface are discussed in Section 4.0.

Known Benefits and Limitations

The bathtub approach, whether based on a single-value or a varying water surface, is a relatively quick approach of mapping areas that could be potentially affected by future sea level rise. It is a method used by many government agencies, including NOAA, to provide initial assessments of inundation vulnerability and potential impacts to coastal communities from rising seas. But, most importantly, it provides valuable information that helps initiate discussions among stakeholders and decision makers on what issues to consider as they plan and adapt to sea level rise.

SFWMD, the Compact Counties and their partners, acknowledge that the modified bathtub modeling approach has limitations. For instance, it assumes that land geomorphology, tidal surface variability and other conditions remain constant as the landscape is "inundated", and that there are no additional hydrodynamic effects during storm surges. As a result, the modified bathtub method does not take into account the role of other key factors, which could either exacerbate or lessen future impacts. These factors include anthropogenic activities (e.g. activities caused by humans); higher groundwater levels; coastal barrier island migration; changes in sedimentation rates and deposition patterns; changes in tidal hydraulics due to land geomorphology changes and physical barriers; and other weather/ocean factors (e.g. storm surge, wave activity and anomalous events). (Marcy et.al. June 2011; NOAA CSC August 2010b; NOAA NOS September 2010).

While the scientific community develops and improves more robust models, the modified bathtub modeling approach recommended by NOAA CSC has provided the Compact and SFWMD with reasonable and useful planning-level estimates of areas in SE Florida vulnerable to sea level rise.

4.0 MHHW Tidal Surface

To estimate areas vulnerable to SLR inundation, the input land and water surface elevations must be compared using the same vertical reference system (vertical datum). As recommended by NOAA, the Compact selected the Mean Higher High Water (MHHW) tidal datum for the simulated water surfaces. MHHW represents the average height of the higher high water of each tidal day observed over the National Tidal Datum Epoch (NTDE). Because DEM land elevations are based on the NAVD88 orthometric datum and tidal datums are defined relative to local mean sea level (LMSL), the simulated tidal water surface must be adjusted to NAVD88 and extended inland. (NOAA CSC, October 2007). However, generating a regional tidal surface in NAVD88 is complex for South Florida. Based on NOAA measurements and benchmarks at several long-term and short-term tide stations along the South FL coast, the conversion values from LMSL (and hence from MHHW) to NAVD88 have considerable variability when they are compared at a regional scale, especially within bays and intracoastal areas. Therefore, the Compact agreed that using a single-value conversion factor and a flat water surface was not appropriate for regional SLR analysis. (Gassman, August 2010). Refer to Figure 5 for examples of tidal datum values that reflect this variability, using data provided by NOAA CO-OPS in July 2010.

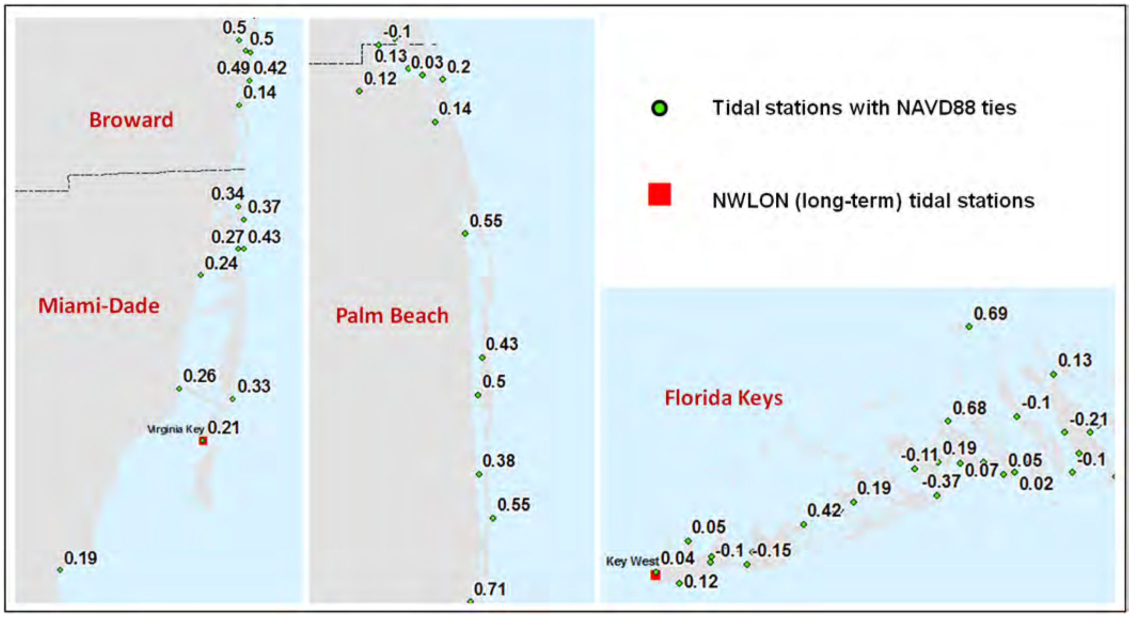


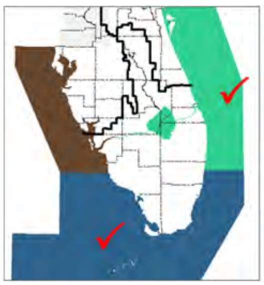
Figure 5 - MHHW tidal datum values in NAVD88 (ft) at locations with geodetic ties
This figure depicts MHHW tidal datum elevations, referenced to NAD88, in feet, at locations that have two or more valid NGS NAVD88 elevations (9 mm tolerance). Data was provided by Jerry Hovis of NOAA CO-OPS in July 14, 2010. Data is also available from NOAA's Tides & Currents website (http://tidesandcurrents.noaa.gov) or CO-OPS SOAP web services (http://opendap.co-ops.nos.noaa.gov/axis/).

To assist SFWMD and the Compact with SLR inundation vulnerability mapping, NOAA CSC developed the base reference MHHW tidal water surface in NAVD88 feet for the SE Florida Compact region. The base water surface provides an estimate of the current, spatially-varying MHHW levels (e.g. without added SLR) and serves as the starting point from which future SLR scenarios can be developed. Due to the complex tidal datum regional variability described above, NOAA CSC developed a spatially-varying MHHW surface using the regional transformation grids that are part of NOAA's National Ocean Service (NOS) VDatum transformation software.

VDatum is a software tool that transforms elevations among several vertical datums, including from tidal datums (e.g. MHHW) to orthometric elevations (e.g. NAVD88). It uses transformation grids developed from observational data, hydrodynamic numerical models and spatial interpolation techniques. For a given model region, VDatum relies on two spatially-varying fields to make its calculations: one for a given tidal datum relative to local mean sea level (LMSL) and the other for the Topography of Sea Surface (TSS), which represent NAVD88 elevations relative to LMSL. The tidal datum fields are derived from simulated water level time series data using the ADvanced CIRculation (ADCIRC) hydrodynamic model which uses unstructured triangular grids. The modeled tidal datums are verified and corrected by applying error fields from comparisons with observational water level data. The final tidal datum fields are interpolated into a regularly structured VDatum marine grid. Finally, for the same marine grid, the

NAVD88-to-LMSL field is derived by fitting tidal model results to tidal bench marks leveled in NAVD88 or calculating orthometric-to-tidal datum relationships at NOAA tidal gauges. (Yang, 2010). Additional details on how the VDatum transformation grids for South Florida were generated will be publicly available in a forthcoming NOAA Technical Memorandum to be titled "*VDatum for Coastal Waters from the Florida Shelf to the Southern Atlantic Bight: Tidal Datums, Marine Grids, and Sea Surface Topography*". Once completed, the publication will be accessible at: http://vdatum.noaa.gov/docs/publication.html.

To develop the base reference MHHW tidal surface, NOAA CSC first merged two VDatum regional transformation grids (Figure 6) and converted the MHHW values to NAVD88 feet. Figure 7 depicts the variability of the MHHW tidal surface, in NAVD88 feet, from one of the regional VDatum grids in the Florida Bay region (FLsouth01).



FLGAeast01:
Florida/Georgia - Fort Lauderdale FL to Sapelo Island GA

FLsouth01:
Florida - South Florida, Naples to Fort Lauderdale FL, and Florida Bay

Figure 6 - VDatum Regional Transformation Grids Used by NOAA CSC
NOAA release date: 04/09/2010

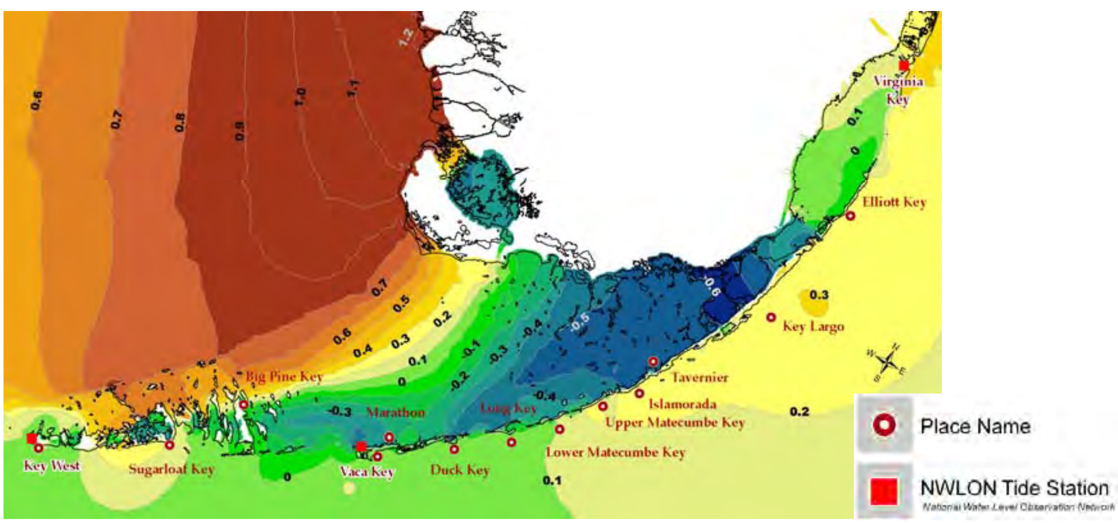


Figure 7 - VDatum MHHW Tidal Variability by Florida Bay, in NAVD88 ft
(FLsouth01) - Without inland extrapolation

By design, the VDatum transformation grids do not extent far inland as there are no tidal stations to validate such surface. Therefore, NOAA CSC conducted additional processing steps in order to extrapolate the tidal surface inland. To lessen unrealistic bias, tidal values by Lake Okeechobee and its largest connected waterways were not included in the extrapolation. The process also included the use of the Nearest Neighbor interpolation method. Figure 8 depicts the final extrapolated MHHW tidal surface, in NAVD88 feet, that was generated by NOAA CSC. It is illustrated using the same elevation color classification scheme as in Figure 7. Additional processing details can be found in the FGDC-compliant metadata in Appendix A.

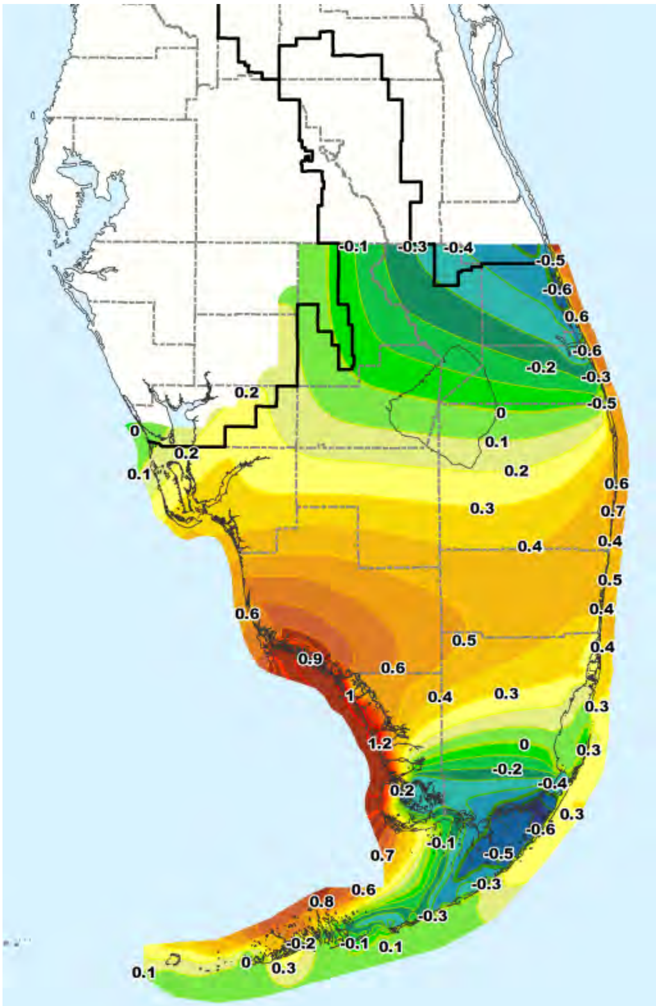


Figure 8 – NOAA CSC's MHHW Tidal Surface, Version 1 (After Inland Extrapolation)
(NAVD88 in ft) – 1500-ft cell size
This figure depicts the MHHW tidal surface, generated by NOAA CSC, after inland extrapolation. Values were color-classified in 0.1-ft elevation intervals. Contour lines, and associated labels, were added to provide a frame of reference and illustrate the distribution of the values in the resulting MHHW tidal surface.

Extrapolating tidal datums inland is challenging because tidal datums have no physical meaning inland and cannot be verified with field data, until that inland location becomes inundated by the ocean tides. Because of the lack of such field data, it is also difficult to quantify this uncertainty and reflect it in the mapped SLR inundation scenarios. As mentioned earlier in this section, part of this complexity is due to the co-dependent dynamics of tides to other natural and human-induced coastal processes, including coastal land erosion, vegetation migration and engineering structures. In some SLR scenarios, it is also possible that the local tide patterns that were used by NOAA to develop the current VDatum transformation grids may no longer be completely valid on a future SLR scenario. (NOAA NOS, September 2010). Other issues discussed among Compact members, but difficult to resolve, were how far inland to extrapolate the VDatum MHHW tidal grid and whether the levees by the Water Conservation Areas could serve as realistic hydrologic barriers. (Gassman, September 2010).

Despite the uncertainty associated with the extrapolated MHHW base tidal surface, assumptions had to be made in order to evaluate potential inundation vulnerability from SLR and equip the Compact coastal communities with preliminary vulnerability data that would help them as they plan and adapt as a region to the likely future effects of SLR. As with any other scientific modeling, these concerns have been acknowledged by providing documentation of the selected methods, and the associated assumptions and uncertainties.

5.0 NOAA CSC Uncertainty Mapping Method

5.1 Z-Scores and Cumulative Probability

SLR inundation vulnerability was mapped by using a methodology that took into account some of the estimated uncertainties associated with land elevation and the tidal water surfaces. This method was proposed by NOAA CSC and agreed to by the Compact. As described below, the methodology involved the calculation of a standardized variable known as Z-score in grid cells that covered the study area and associating these with estimated probabilities. From this, it was possible to map vulnerable areas at two ranges of probability: between 25 to 75% and greater than 75%. Using cumulative probability, we estimated the likelihood that land elevation at a particular location would be less than or equal to a given future SLR elevation scenario. Because there are other factors that help determine if a particular area will or will not be inundated by a higher sea level, it is important to note that the likelihood calculated by this process only estimated the probability that a particular land area is vulnerable to the effects of SLR inundation due its current elevation relative to the given future SLR elevation, using the "bathtub" approach described in Section 4.0. The probability of inundation may be higher or lower when other factors are taken into account, such as hydraulic barriers and increased groundwater table.

The main assumption behind NOAA's uncertainty mapping method is that if vertical errors in the source elevation data (land and tidal water surfaces) follow a normal distribution (i.e. the traditional bell-shaped curve), it is possible to “standardize” a variable (i.e. an elevation value) to get what is referred to as a Z-score, which is the number of standard deviations of that value from the mean of the distribution. Z scores are typically calculated by re-scaling (i.e. standardizing) the distribution such as that the mean (μ) is 0 and the standard deviation (σ) is 1. To standardize values, the following equation is used.

$$Z = \frac{x - \mu}{\sigma}$$

The characteristics of a standard normal distribution are such that any given Z score can be easily associated with a cumulative probability percentage, which refers to the probability that a variable is less than or equal to a specified value. Because of this well-established relationship, standard normal tables are commonly published to help scientists quickly reference z scores to cumulative probability. This relationship is also depicted in the figure below (Fig 9).

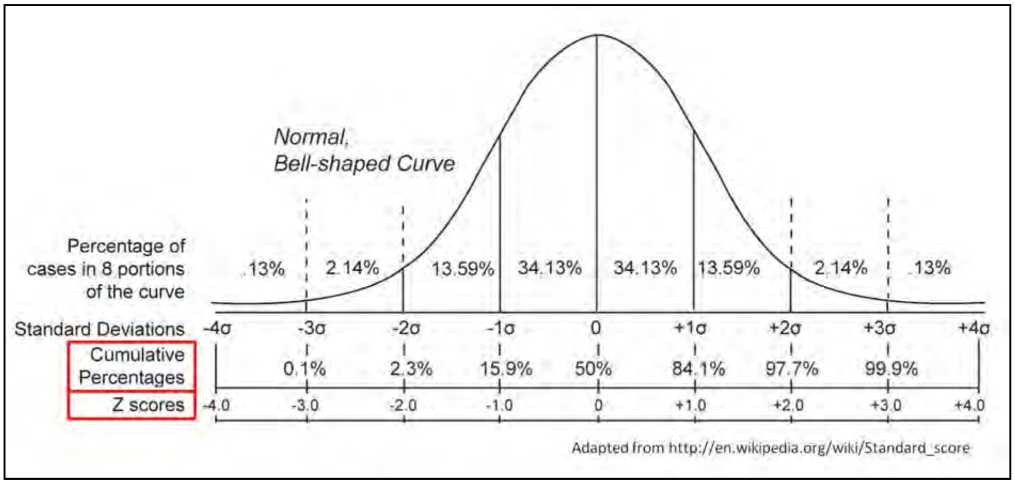


Figure 9 - Standard Normal Distribution

To apply this statistical method to SLR inundation vulnerability mapping, several key assumptions were made. It was assumed that vertical errors are normally distributed. It was also assumed that there is no bias in the error distribution and that the standard deviation is equivalent to the Root Mean Square of the Errors (RMSE) in the elevation data sources. Since there are two elevation sources in SLR inundation mapping, the total RMSE is calculated from the individual RMSE value of the LiDAR (land) elevation surface and of the MHHW tidal water surface. To simplify uncertainty-based mapping, it was assumed that the RMSE in both input surfaces is uniform across the analysis area (i.e. constant). This assumption could be reevaluated in a future effort. The source of the RMSE values used by SFWMD to calculate Z scores are described below.

RMSE of the Land Surface (LiDAR)

As recommended by NOAA CSC, the RMSE for the LiDAR-based land surface was taken from the FDEM LiDAR project specifications, which required all contractors to meet an RMSE of 0.30 feet for open terrain. (FDEM 2007). It is possible that this value is too generous for areas where LiDAR bare earth elevations are likely less accurate, such as by wetlands, mangrove forests and other heavily vegetated regions.

RMSE of the MHHW Tidal Surface

Based on NOAA CSC recommendations, the RMSE for the MHHW tidal water surface was taken from the larger of the maximum cumulative uncertainties (MCU) calculated and published by NOAA for the two VDatum regional grids (FLGAeast01 and FLsouth01) used by CSC to generate the merged and inland extrapolated tidal water surface. It is important to note that this RMSE value does not account for added uncertainty introduced from the inland extrapolation of VDatum grids, which, as described in Section 4.0, is difficult to quantify. The FLGAeast01 regional grid had the larger published MCU, which was 10.8 cm (~ 0.35 feet). The MCU of each regional VDatum tidal surface is a based on a set of calculations that take into account the estimated individual uncertainties of various transformation steps and data sources involved in converting from the International Terrestrial Reference Frame (ITRF) ellipsoid, to NAD83, to NAVD88, to LMSL and finally to the tidal datum with the greatest uncertainty. This process is best described and illustrated at the following NOAA VDatum website, which is also where the MCUs of the VDatum regions are reported: vdatum.noaa.gov/docs/est_uncertainties.html.

Calculation of Z-Scores Using GIS Tools

The Z equation is applied at each grid cell (x,y) of the analysis region with the use of GIS-based raster math tools, with the land and water elevation surfaces as input values. The output of this process is a raster with the standard Z score at each grid cell (x,y). The formulas are illustrated in the figure below (Fig 10).

$$Z - \text{Score}_{(x,\,y)} = \frac{\text{Tidal Water Surface}_{(x,y)} - \text{Land Elevation}_{(x,y)}}{\text{RMSE}_{(\text{inund})}}$$

where:

$$\text{RMSE}_{(\text{inund})} = \sqrt{\underbrace{\text{RMSE}^2_{(\text{land})}}_{\text{LiDAR (Topo) DEM}} + \underbrace{\text{RMSE}^2_{(\text{water})}}_{\text{MHHW Tidal Surface}}}$$

$$= \sqrt{0.30^2 + 0.35^2} = 0.46 \text{ ft}$$

Figure 10 - Z-Score Formula Applied in GIS Raster Tools (define the variables in the figure)

To help demonstrate how the method was applied to the study area, the example below (Fig 11) depicts a future SLR scenario where the MHHW tidal surface has an elevation of 7 ft. For simplicity, we assume that only land elevation has errors. Each point represents a cell in the input land surface grid, with a given discrete elevation value that varies from 4.5 to 9 ft. The RMSE of the land elevation is assumed to be 2.5 ft. The graph at each cell point depicts a normal distribution in which the land elevation is assumed to represent the mean. At each cell, the Z score is re-calculated and associated with a cumulative probability. For instance, at cell A, the land surface is depicted as having an 84% probability of being at an elevation that is at or below the given SLR scenario elevation (7 ft); whereas at cell B, the land surface has equal probability of being either above or below that given SLR elevation. When there are errors in both the land surface and the water surface (MHHW), the same concept holds, except that the RMSE of inundation would incorporate the RMSE of both the land and the water surfaces (refer back to Fig 10).

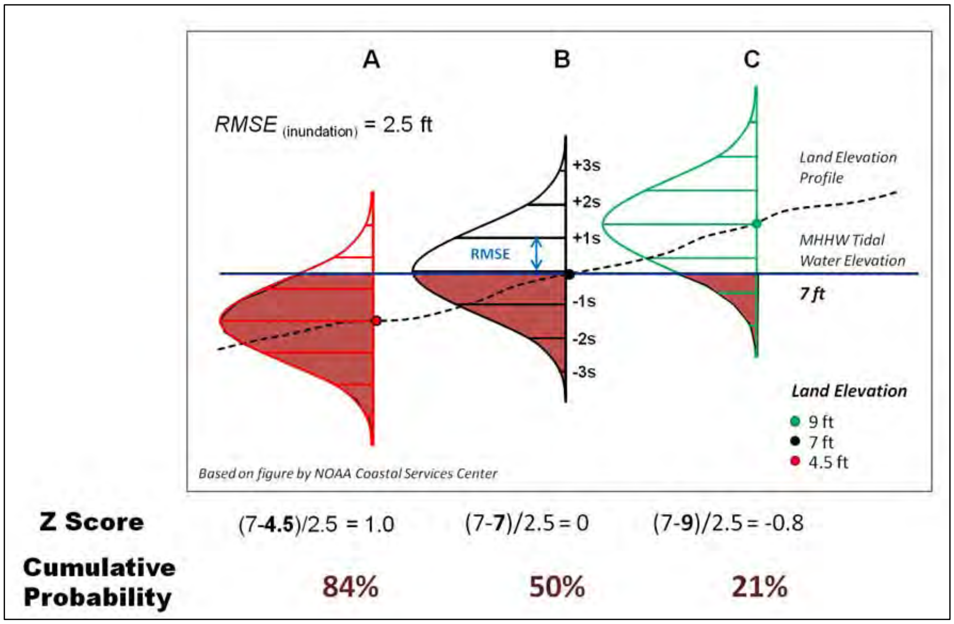


Figure 11 – Z-Score and Cumulative Probability Calculation Example

For additional details about NOAA CSC's Z-score based methodology for portraying inundation uncertainty, refer to their publication titled "*Mapping Inundation Uncertainty*", dated August 2010.

5.2 "Compact" Inundation Vulnerability Reporting

To facilitate the reporting of the statistical results to the public and other stakeholders, the Compact Counties agreed to employ public-friendly terminology to convey the likelihood of inundation vulnerability. Translating statistical results into simpler, public-friendly terminology is common practice among researchers and frequently employed by many government agencies, including NOAA. To accomplish this, the calculated cumulative probabilities 25% or higher were re-classified and mapped into two ranges of probability and associated with a user-friendly term and a common map color, as illustrated below.

Table 2 - Inundation Vulnerability Terminology

Compact's Map Color	Compact's Public-friendly Terminology	Probability of Inundation Vulnerability Statement	Z Scores
	Possible	25% to 74.9% probability that the grid cell (land area) has an elevation less than or equal to the MHHW tide level	Z >=-0.67 and <+0.67
	More Likely	75% or greater probability that the grid cell (land area) has an elevation less than or equal to the MHHW tide level	Z >=+0.67

The classification of SLR vulnerability into these probability groups also helped the Compact Counties to estimate a numerical range of vulnerability, rather than an absolute number, when results of their analysis were quantitative in nature (e.g. number of acres). When this was applied, a low and high estimate was calculated. For instance, one of the parameters calculated by the Compact counties was the total acreage of individual land use categories that would be vulnerable to SLR inundation (due to the land area being at an elevation less than or equal to the MHHW tide level). In this case, the low and high estimates can be interpreted as follow:

- *low estimate* = # of acres of a particular land use category with a 75% or greater probability
- *high estimate* = # of acres of a particular land use category with a 25% or greater probability (possible + more likely)

6.0 SLR Inundation Vulnerability Surfaces

Using GIS tools, several grid layers were generated to help analyze areas that could be vulnerable to SLR inundation. They were generated using the data and methods described in earlier sections of this report, including SFWMD's 50-ft land surface DEMs, NOAA's MHHW tidal surface and NOAA's recommended uncertainty mapping methods. For manageability purposes, the Compact region was sub-divided into 5 analysis areas, roughly following county borders and FDEM project group areas (Fig 12). Monroe County was subdivided into two areas, one for inland Monroe (MR) and the other for the Florida Keys (FK). The inland Monroe (MR) analysis data was not used by the Compact Counties in their vulnerability analysis.

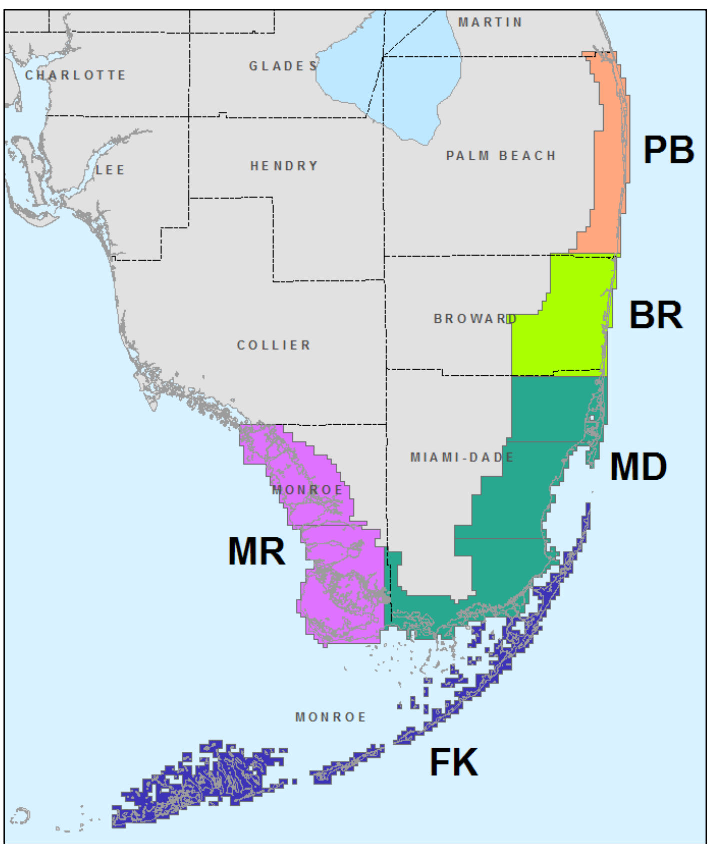


Figure 12 - SLR Vulnerability Analysis Areas

The results of each analysis area were stored in a separate corresponding file geodatabase. For each analysis zone, five grid layers were generated for each SLR scenario (1, 2 and 3-ft feet above current MHHW) for a total of 15 layers. In addition, one baseline layer (0-ft SLR) was generated, which represents areas where the land elevation is at or below the current MHHW tidal surface elevation. This "baseline" grid layer probably includes existing inland water bodies and other low-lying areas near the coast that are already under the influence of the current MHHW tide. The figure below (Fig 13) depicts an example of the grid layers stored in each geodatabase. For technical details on how these layers were generated, refer to the example geoprocessing log in Appendix B. A brief explanation is provided below on what each of these layers represent.

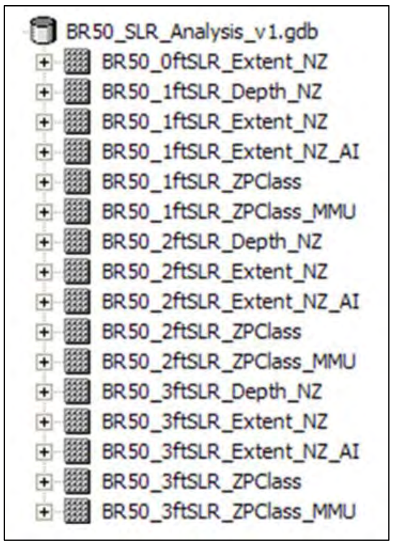


Figure 13 – Example Output Grid Raster Layers Generated for each Analysis Zone
In this example, BR refers to Broward County. Refer to Figure 12 where the prefix for each analysis region is shown.

Vulnerability Grids Using Z-Score/Cumulative Probability

The main output of the analysis were grid layers representing the probability of areas being at an elevation less than or equal to the MHHW tide level of each SLR scenario. The development of these layers first involved generating grids of Z scores using the input variables and math logic described in Section 5.0. The Z-score grids were then re-classified into new grids that were assigned one of two possible integer values, using a conditional statement that evaluated cells representing two ranges of cumulative probability based on the corresponding Z scores listed below.

- A value of 25 was assigned when a Z score was equal to or greater than -0.67 but less than 0.67 (representing ~ 25% to 74.9% probability)
- A value of 75 was assigned when a Z score was equal to or greater than 0.67 (representing ~ 75% or greater probability)

Table 3 describes the two layers that were generated for each SLR scenario, using the 1-ft SLR as example. The only difference between these two layers is that for one of them the Compact's Minimum Mapping Unit (MMU) of ½ acre was applied. Again, refer to Appendix B for additional processing details.

Table 3 - SLR Vulnerability Probability Grid Layers

Grid Layer Name	Description
BR50_1ftSLR_ZPClass	*Probability of areas at or below MHHW + 1 ft of SLR.* Grid cells values are 25, 75 or NoData. This layer was generated by reclassifying the Z-score grid into 2 values to represent the two cumulative probability classes: 25 -> means 25% to 74.9% probability (z >= -0.67 and <0.67) 75 -> means >= 75% probability (z >= 0.67)
BR50_1ftSLR_ZPClass_MMU	*Probability of areas at or below MHHW + 1 ft of SLR that are greater than ½ acre.* Similar as grid layer above, except that it excludes areas that did not meet the Minimum Mapping Unit (MMU) of ½ acre. Cell values represent same as above. This layer was generated by excluding cells that, when connected using a neighborhood of 8 cells, did not meet the MMU. For instance, in the case of a 50-ft grid, this excluded areas of less than 9 connected cells. 50-ft cell = 2,500 sq ft ½ acre = 21,780 sq ft = 8.71 cells (21780/2500) ≈ 9 cells

Figure 14 is an example of how these layers can be used to illustrate SLR vulnerability. Some of the coastal land areas depicted in this map in purple (with probability >= 75%) may include areas already under the influence of current MHHW conditions, such as coastal mangroves.

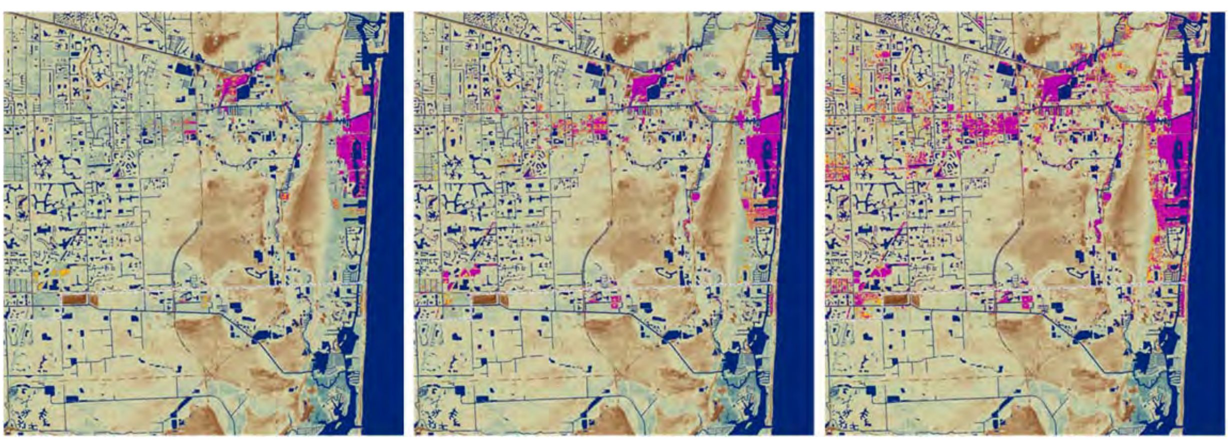


Figure 14 - Example SLR Vulnerability Probability for 1 to 3 ft above MHHW
This figure depicts the probability of vulnerability for three SLR scenarios. Existing water bodies (e.g. ocean, intracoastal waterway, lakes and canals) are shown in dark blue, over the vulnerability grids. Water layers were taken from FDEM LiDAR breaklines and SFWMD's ArcHydro layers. The underlying basemap is a shaded relief DEM from the FDEM LiDAR data, with darker browns representing higher elevations.

75% or greater (More Likely)
25% to 74.9% (Possible)

Vulnerability Grids without Accounting for Elevation Data Uncertainty

An additional set of grid layers were generated for each SLR scenario, but without using Z scores. These layers were derived without taking elevation uncertainty into account or without applying a minimum mapping unit. Table 4 describes these grid layers. Appendix B provides more processing details.

Table 4 - SLR Grid Layers Assuming No Elevation Uncertainty

Grid Layer Name	Description
BR50_0ftSLR_Extent_NZ	*0-ft SLR Extent (Baseline), assumes no sea level rise.* Grid cells with a value of 1 represent areas where the elevation is at or below the MHHW tidal surface (without adding any SLR). This layer probably includes inland water bodies and other low-lying areas near the coast that are already under the influence of the current MHHW tide. Therefore, this layer could be helpful for verifying the extrapolated MHHW tidal surface itself, such as evaluating how well it represents areas known to be affected by current MHHW conditions.
The layers below were generated for each SLR scenario.	
BR50_1ftSLR_Extent_NZ	*1-ft SLR Extent.* Grid cells with a value of 1 represent areas where the elevation is at or below the MHHW tidal surface plus 1-ft SLR.
BR50_1ftSLR_Extent_NZ_AI	*1-ft SLR Added Extent, excludes areas vulnerable at 0-ft SLR.* Grid cells with a value of 1 represent areas vulnerable to 1-ft SLR, but exclude areas already at or below current MHHW (0ft SLR). AI -> stands for the added "inundation". It was generated by subtracting the 0-ft layer from the 1-ft SLR layer.
BR50_1ftSLR_Depth_NZ	*Depth in feet of the 1-ft SLR Extent.* More appropriately, this grid layer represents how many feet above or below is the land surface (DEM cell value) from the MHHW tidal surface with the added SLR. When the land surface is below the water surface, the values are positive and represent the elevation difference. This layer was created as a pilot and was not used by the Compact Counties for their vulnerability analysis. It does not include the influence of the 0-ft SLR conditions.

Figure 15 is an example of how some of these layers could be used to depict how vulnerability varies by SLR scenario.

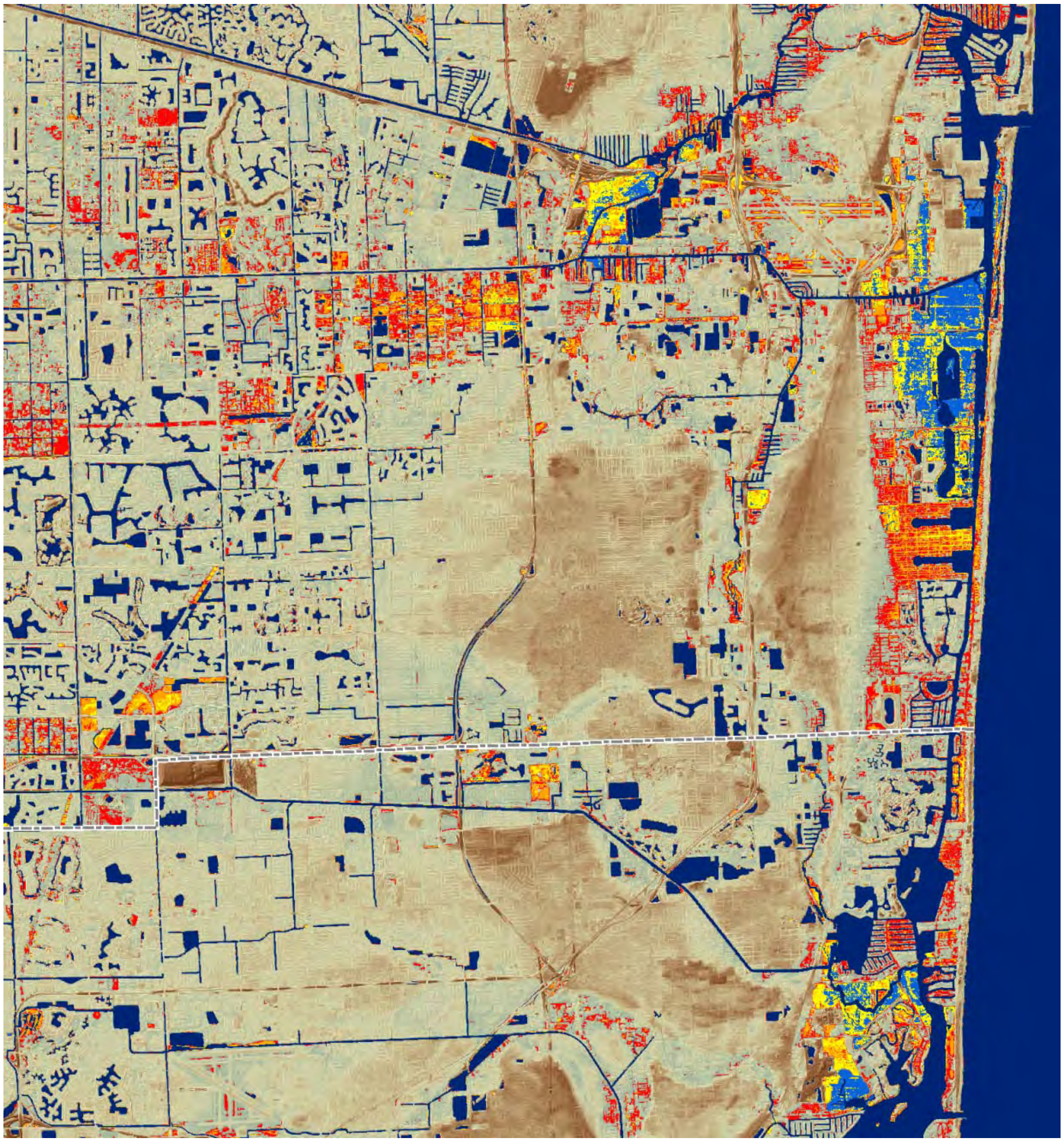
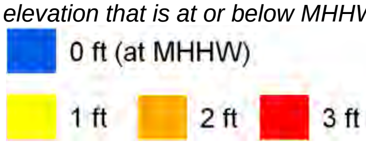


Figure 15 - SLR Vulnerability at 1 to 3-ft above MHHW (Assuming No Elevation Errors)
Assuming no uncertainty in elevation sources, this figure is an example of analysis output showing areas at an elevation that is at or below MHHW with the following additional feet of water:



7.0 Conclusions and Recommendations

Although SLR mapping efforts have been conducted for South Florida by others, most of the earlier efforts were based on methods that used less accurate and detailed topographic and water surface data. Very few took into account, or even acknowledged, the vertical uncertainty of the input elevation sources. In several cases, technical documentation associated with those efforts is limited or hard to find. But, perhaps most notably, none of them were the result of a coordinated regional effort, led by four neighboring counties in FL that worked closely with many state, federal, academia and non-profit partners, to come up with an improved estimate of the region's vulnerability to sea level rise.

In support and in partnership with the Southeast Florida Regional Climate Change Compact and NOAA, SFWMD generated SLR vulnerability inundation layers for three possible sea level rise scenarios: 1 foot, 2 feet and 3 feet above current MHHW tide levels. These datasets were used by the Compact counties to do a preliminary assessment of the potential impacts of SLR.

As noted carefully and copiously in this technical report, there are known limitations and uncertainties associated with the analysis conducted. Neither SFWMD, nor the Compact Counties, assume that their recent SLR vulnerability mapping and analysis would be the last attempted by them or other agencies. The science and modeling associated with sea level rise studies are complex and continually evolving. Therefore, none of the results presented should be taken, quoted or assumed as absolute or final. But, hopefully, they are an improvement to other earlier efforts.

One of the recommendations of the Compact's Regional Climate Change Action Plan is to continue to evaluate and improve SLR vulnerability mapping and analysis methods. The rest of this section provides suggestions and recommendations that could improve future SLR inundation vulnerability mapping, as well as expand the geographic extent of the study region to other coastal communities in South Florida.

Topographic/ Land Surface DEM

- *Expand the geographic extent of the study region by carefully merging the FDEM LiDAR data with other best available topographic data.*

Due to time and resource constraints, the land surface DEMs used in the SLR analysis were solely based on the FDEM LiDAR data. Although this dataset included most of the urban coastal areas within the Compact region, it did not cover the full extent of each Compact county. As a result, those areas were not included in the SLR inundation vulnerability mapping conducted by SFWMD. Unfortunately, developing a merged DEM from multiple topographic sources is typically a complex process. Overlapping and adjacent datasets seldom "match" because they were often collected at different time periods and using different technologies, specifications and vendors. Therefore, collecting additional survey points is often necessary where the datasets overlap to help determine the best methods to merge the datasets and calculate the vertical accuracy of the merged areas. Those methods could include making vertical adjustments to one dataset, deciding to omit one, or using filtering/smoothing algorithms to reduce the elevation differences among the joining datasets.

- *Improve the quality of the existing best available topographic data and derived DEMs.*

DEM conditioning is typically necessary to address remaining artifacts that do not properly depict water connectivity and surface water flow patterns. Unfortunately, this can be time consuming and cost-prohibitive. Although GIS tools could automate some aspects of this process, manual edits and additional field data are often necessary to resolve some areas. For instance, SFWMD has developed filtering and decorrugation algorithms that help reduce and smooth 'LiDAR" banding artifacts. However, even after applying automated processes like these, it may still be advisable to validate accuracy with independent field data.

MHHW Tidal Surface

- *Improve the MHHW tidal surface landward extrapolation by using NOAA's latest guidance and data.*

The regional MHHW tidal surface generated by NOAA CSC in July 2010 for the Compact could probably be improved using NOAA's most recent guidance and data. For instance, since that original work, CSC has been experimenting with Euclidean Distance Allocation functions to take the landward-most VDatum grid values and extending them inland perpendicularly to the coastline. They have found that this reduces small errors that may have been introduced by applying the nearest neighbor interpolation across the FL peninsula. It may also be valuable to explore the usability of newer data products generated by NOAA CSC. As part of their web-based SLR map viewer project, CSC has generated a new MHHW extrapolated tidal surface. (Doug Marcy, personal communication, January 2012).

- *Refine, if practical, the MHHW tidal surface along the Florida Keys and other narrow coastal areas.*

In some narrow stretches of coastal land, such as the Florida Keys, the MHHW tide surface is complex and quite variable. To smooth the transition of landward tidal values, it may be beneficial to generate an extrapolated tidal surface with a smaller cell size. The cell size of the original tidal surface generated by CSC for the Compact may have been too large (1500-ft), and it generated a few abrupt inland tidal elevation differences in some areas of the Keys.

Inundation Mapping Methods

- *Consider whether developing and applying spatially-variable error fields for both the land and water surfaces would be practical and beneficial to future SLR vulnerability mapping.*

As described in Section 5, the SLR vulnerability raster surfaces were generated by applying a single, but different, uncertainty value to both the land and water surfaces across the entire study area. This assumption may not be valid in all land areas, such as those covered by wetlands and coastal mangroves. Applying the FDEM RMSE specification value of 0.3 feet for bare earth may have been too generous for these areas. Likewise, the source VDatum tidal grids have different and spatially-variable uncertainty values. The effort to generate and apply more robust error rasters should be outweigh by its potential benefit. Also, there is possibly a larger error which is far more difficult, if not impossible, to take into account quantitatively, which is the error associated with extrapolating the VDatum grids landwards, as there is no field data to help determine the accuracy of such extrapolation.

- *Address the role of inundation depth in estimating the degree of vulnerability.*

The degree of SLR vulnerability is also related to how large is the elevation gradient between the current land surface and the simulated SLR water surface. Areas with higher depth of inundation might experience more significant impacts.

Other Suggestions

- *Follow-up with NOAA CO-OPS to determine if there are opportunities for expansion and improvement of the current tidal station network in South Florida.*

In 2008, NOAA CO-OPS published a study that identified NWLON tidal station network gaps in South Florida. Per NOAA, the study identified “the geographic region for each NWLON station within which a datum computation at a subordinate station with a 3-month time series will be accurate to less than or equal to 0.12 ft.” This is the target criterion they believed would “ensure the accuracy of datum determination at subordinate locations… [and] meet most user requirements.” Using this criterion, they identified “gaps for consideration of new priority NWLON station requirements”. (Gill, March 2008).

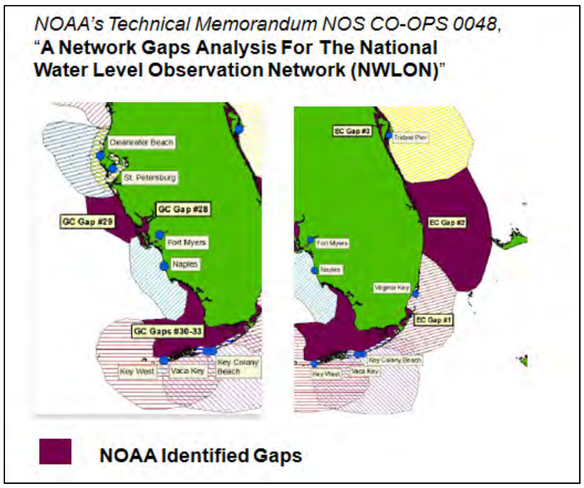


Figure 16 – NWLON Network Gaps Identified by NOAA
Credit: NOAA CO-OPS. (Gill, March 2008).

NOAA also conducted a preliminary assessment of the tidal datums along the Florida Coast in support of the VDatum project. In their evaluation, they proposed additional ellipsoidal and orthometric datums, installation of new stations and reoccupation of several historical stations. (Hovis, April 2010). The Compact may wish to follow-up with NOAA to identify if funding will be available in the future to implement these recommendations.

- *Validate SLR inundation vulnerability maps by using observations gathered from exceptional seasonal high tides.*

To help validate and improve SLR vulnerability mapping, the Compact could take advantage of future exceptional seasonal high tides that "mimic" what future SLR scenarios may look like. The data collected from these events could help validate and improve future mapping efforts.

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ABBREVIATIONS

Compact	Southeast Florida Regional Climate Change Compact
CO-OPS	NOAA's Center for Operational Oceanographic Products and Services
CSC	NOAA's Coastal Services Center
DEM	Digital Elevation Model
FDEM	Florida Division of Emergency Management
FDOT	Florida Department of Transportation
FEMA	Federal Emergency Management Agency
GIS	Geographic Information Systems
GPS	Global Positioning System
HAED	USGS High Accuracy Elevation Dataset
LiDAR	Light Detection and Ranging
LMSL	Local Mean Sea Level
MCU	Maximum Cumulative Uncertainty
MHHW	Mean Higher High Water
NED	National Elevation Data
NOAA	National Oceanographic and Atmospheric Administration
NAVD88	North American Vertical Datum of 1988
NGS	National Geodetic Survey
NGVD29	National Geodetic Vertical Datum of 1929
NWLON	National Water Level Observation Network
NTDE	National Tidal Datum Epoch
QA	Quality Assurance
RMSE	Root Mean Square Error
SD (σ)	Standard Deviation
SE FL	Southeast Florida
SLR	Sea Level Rise
SFWMD	South Florida Water Management District
TIN	Triangulated Irregular Network
TSS	Topography of Sea Surface
USGS	United States Geological Survey
USACE	United States Army Corps of Engineers