



Review & Evaluation of FEMA's Coastal Flood Risk Study

Storm Surge, Wave Model & Flood Map Evaluation (Deliverable 5.1)

Task Order #1778-01

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Executive Summary

The National Flood Insurance Program (NFIP) is a federal program that provides flood insurance to property owners within participating communities. Palm Beach County and a number of its communities participate in the program. The Federal Emergency Management Agency (FEMA) is responsible for administering the NFIP and, as such, periodically updates information on the flood hazards. The updated information is incorporated into FEMA's Flood Insurance Study (FIS) and Flood Insurance Rate Maps (FIRM) for a given study area.

FEMA is in the process of updating the FIS for the South Florida study area with the Coastal Flood Risk Study (SFL study), which reevaluated the coastal flood hazard originating from the Atlantic Ocean. Palm Beach County, along with Broward, Miami-Dade, and Monroe Counties, is located within the SFL study area. While FEMA's SFL study leveraged numerical modeling and engineering analyses to better define the coastal flood risks associated with storm surge, a technical review of FEMA's model setups, inputs, outputs, and other provided data identified specific elements to improve the accuracy, consistency, reliability, and repeatability of the study with respect to Palm Beach County. The major elements presented herein are summarized below.

- SWAN+ADCIRC Model Validation [Section 2]: FEMA's extensive model validation resulted in reasonable agreement with measured astronomical tides. However, there was noticeable differences between measured and modeled water levels of the validation storms that suggest the coastal processes associated with storm surge may not be sufficiently represented by FEMA's SWAN+ADCIRC model. FEMA's model validation was based on 244 measured peak water levels. Only 53% of the measured locations were within a 55-mile offset from the validation storm tracks where storm surges were more likely to be experienced. The model uncertainty within the offset was 2.24 times greater than the uncertainty outside the offset, which suggests that the model was not able to accurately simulate peak water levels within the areas that storm surge were most likely to be experienced.
- Statistical Stillwater Elevations (SWEL) [Section 3]: The wind and pressure fields in Palm Beach County north of Boynton Inlet were not included in FEMA's regional (fine) grid and were modeled at a coarser grid resolution as compared to the rest of the SFL study area. The coarser model grid resolution limits the SWAN+ADCIRC model's ability to represent the storm forcing parameters, and to accurately simulate storm surges for storms making landfall north of and near the boundary of the regional grid. Storm surge was FEMA's basis for the defining the 1% SWEL's of the Atlantic Ocean and within interior water bodies (e.g. Lake Worth Lagoon). The 1% SWEL was used by FEMA to map the inland extent of coastal flooding and in turn define special flood hazard areas (SFHA) shown on their FIRM panels.

Review of FEMA's SWAN+ADCIRC model mesh and modeling of synthetic storms revealed several locations within Palm Beach County where the resolution of the mesh was insufficient to accurately model hydrodynamic and coastal flooding processes. For example, during the synthetic storm that produced the highest water surface elevation (WSE) within the Lake Worth Lagoon, FEMA's model did not allow water to flow out through Boynton Inlet increasing WSE within the lagoon as evidenced by unrealistic changes in the WSE exhibited in the inlet as the storm passed to the north.

The cumulative contributions (adjustments) to the 1% SWEL's offshore of Palm Beach County due to FEMA having included west coast (exiting) storms within the statistical SWEL's and having accepted an increased model uncertainty during model validation were estimated to have increased FEMA's 1% SWEL approximately 1.3 feet. Figure ES.1 shows the 1% SWEL as reported by FEMA (left panel) and the 1% SWEL adjusted (right panel) after removing the cumulative contributions estimated herein (middle panel). In the absence of reperforming FEMA's modeling and given the consistent contributions offshore, a uniform downward adjustment to the 1% SWEL throughout Palm Beach County (and potentially

throughout the east coast of the study area) appears more reasonable than FEMA's approach to applying adjustments. FEMA's approach defined a transition area extending 5 miles north and 5 miles south of the Palm Beach and Martin county line within which the 1% SWEL was adjusted downward 0.85 feet within Palm Beach County and upward 0.85 feet in Martin County. The 1% SWEL adjustments presented herein are based on modeling, information, and data provided by FEMA. Reperforming the SWAN+ADCIRC model is needed to more accurately assess the adjustments to consider the interdependence and spatial variability of improvements to FEMA's modeling, especially within interior water bodies hydraulically connected to coastal inlets.

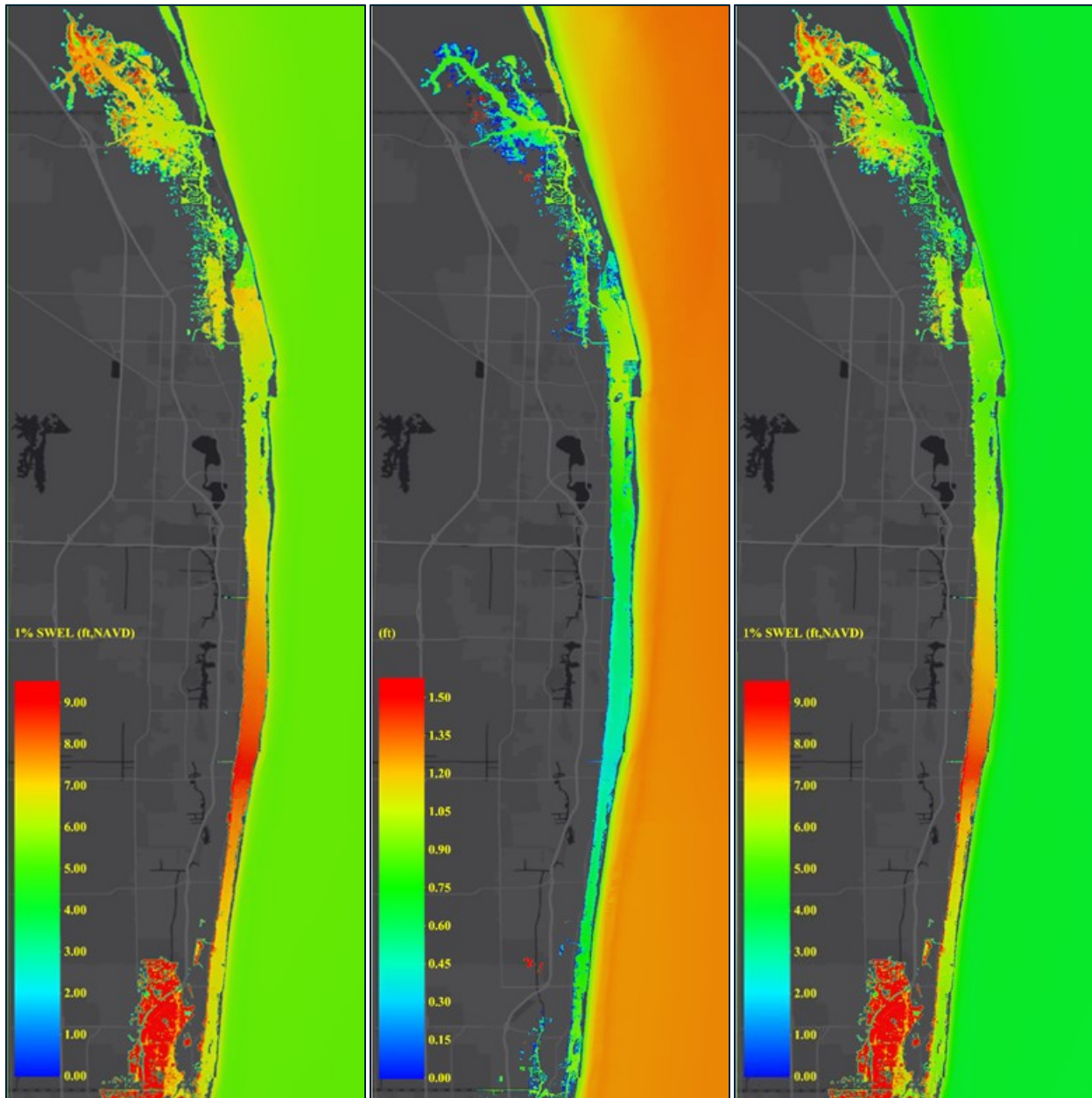


Figure ES.1: 1% SWEL: FEMA (left) – Cumulative Contribution (middle) = Adjusted (right)

- Coastal Hazard Analysis and Mapping [Section 4]: Breaking wave heights were used by FEMA to define the VE zone at only 2 of 170 open coast transects (transects 137 and 138 at MacArthur Beach State Park). A 1.3-foot downward adjustment to the 1% SWEL, as quantified above, would impact the coastal erosion analysis and a dune retreat response would have been identified by FEMA at the transects. A dune retreat response would reduce the northern Lake Worth Lagoon's exposure to Atlantic waves during the 1%-annual-chance event, the inland extent of the VE zone, and in turn may reduce base flood elevations (BFE) of SFHA zones mapped on FEMA's FIRM panels within the lagoon.

Updates by FEMA to SFHA mapping on several FIRM panels upstream of South Florida Water Management District (SFWMD) water control structures as part of the SFL study do not appear consistent or warranted based on the methodologies applied and justification provided by FEMA elsewhere within Palm Beach County.

The information presented herein for Task 5 as well as Tasks 2, 3, and 4 will be compiled in Task 6 to document the key findings, conclusions, and recommendations regarding future coordination with FEMA.

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1. Introduction

The National Flood Insurance Program (NFIP) is a federal program that provides flood insurance to property owners within participating communities. Palm Beach County and a number of its communities participate in the program. The Federal Emergency Management Agency (FEMA) is responsible for administering the NFIP and as such periodically updates information on the flood hazards. The updated information is incorporated into FEMA's Flood Insurance Study (FIS) and Flood Insurance Rate Maps (FIRM) for a given study area.

FEMA is in the process of updating the FIS for the South Florida study area with the Coastal Flood Risk Study (SFL study), which reevaluated the coastal flood hazard originating from the Atlantic Ocean. Palm Beach County, along with Broward, Miami-Dade, and Monroe Counties, is located within the SFL study area.

Baird was contracted by Palm Beach County to provide a technical review of FEMA's SFL study. Task 4 focused on reviewing the SFL study documents produced by FEMA with respect to their applicability and appropriateness to Palm Beach County. Task 5 delves beyond the level of detail contained in FEMA's documents by reviewing model setups, inputs, outputs, and other pertinent data provided by FEMA. The discussion herein is organized into the following broad categories to provide consistency with Task 4.

- SWAN+ADCIRC Model Validation
- Statistical Stillwater Elevations (SWEL)
- Coastal Hazard Analysis and Mapping

It should be noted that the discussion does not attempt to document all elements that were considered during Baird's review nor does it attempt to provide resolutions to these elements, but rather to provide comments that improve the accuracy, consistency, reliability, and repeatability of the study. Coastal analysis and modeling to evaluate the impact and sensitivity of the elements on FEMA's SFL study and the FIRMs are beyond Baird's scope of work.

Reference to FEMA's documents and other data sources are denoted with "[]" and are correlated by the reference numbers assigned in the reference table (Section 6). The table is the same table included in Task 4 to maintain consistency; not all of the listed documents are referenced directly herein.

2. SWAN+ADCIRC Model Validation

The SWAN+ADCIRC model requires validation to “demonstrate satisfactory model performance via comparison of model results with available measured data” [9]. Thus, FEMA’s model validation effort for the SFL study primarily focused on comparing modeled and measured water levels during the following storms:

- Hurricane Betsy (1965)
- Hurricane David (1979)
- Hurricane Andrew (1992)
- Hurricane Georges (1998)
- Hurricane Wilma (2005)

Two types of water level data were considered within the model validation: hydrograph data from gage measurements; and highwater marks (HWM) from post-storm survey measurements. Figure 2.1 was extracted from FEMA’s reports and shows the locations of available water level data for the five selected validation storms used in FEMA’s modeling. The symbols and color scale assigned to the data locations indicate whether the modeled water elevations are above (+) or below (-) the measured water elevations and the magnitudes of the difference between the two. It should be noted that water level data was not available at all locations for each validation storm.

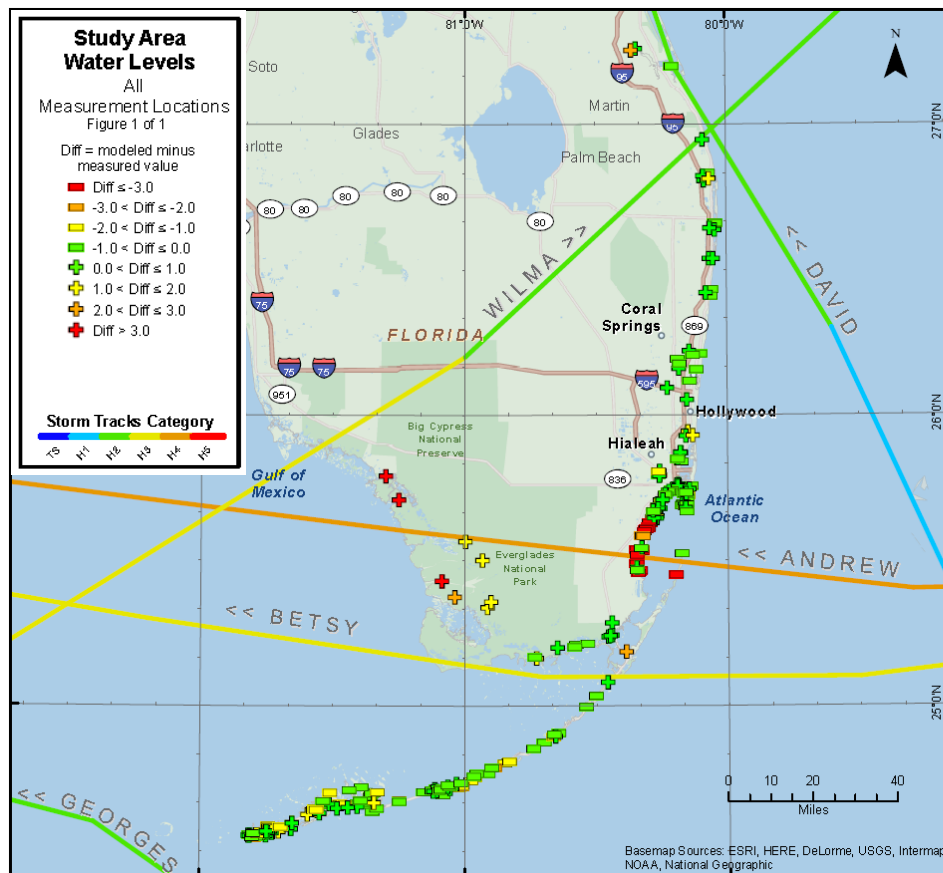


Figure 2.1: Stations with Measured HWM and Hydrograph for All Storms [FEMA, 2019]

Figure 2.2 was extracted from FEMA reports and compares modeled and measured peak water levels. It provides additional detail regarding the validation storm and type of measurement. Solid symbols indicate peak water levels obtained from hydrographs; open symbols indicate HWM.

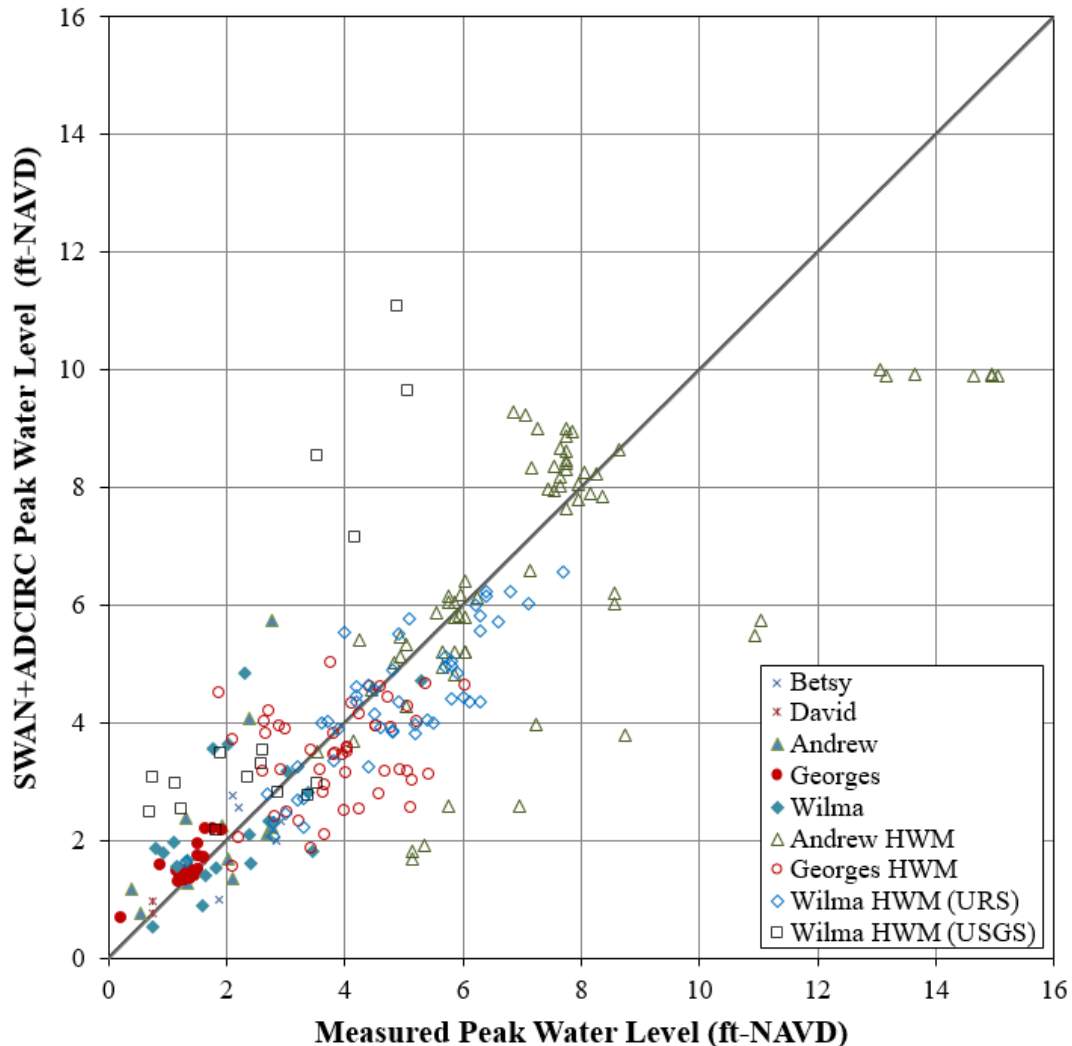


Figure 2.2: Measured-to-Modeled Peak Water Level Comparison for All Storms [FEMA, 2019]

The information presented in FEMA’s figures above is discussed in greater detail below with respect to the proximity of measured water levels to storm tracks, model uncertainty, and gage selection.

2.1 Proximity of Measured Water Levels to Storm Tracks

Storm surge is generally greatest along a storm’s track. As the distance from a storm’s track increases or as the storm tracks away from a particular location, storm surge decreases and changes in water levels become increasingly governed by astronomical tides. **While it is acknowledged that FEMA’s extensive model validation resulted in reasonable agreement with measured astronomical tides, less favorable agreement with measured water levels during the modeled validation storms suggests that the coastal processes associated with storm surge may not be sufficiently represented by the SWAN+ADCIRC model developed by FEMA.** This concept was highlighted in Task 4 by comparing hydrographs of measured

and modeled water levels for a given location for several validation storms. The concept is further developed herein by comparing the model uncertainty (model skill) within a zone defined by offsetting the original validation storm track to both its sides. Model uncertainty is defined as the difference between the modeled and measured peak water levels.

The National Oceanic and Atmospheric Administration (NOAA) provides an online database of historical hurricane storm tracks along with a variety of information. NOAA’s database for the validation storms was reviewed for the distance (radius) from the storm center that hurricane storm force winds extended. Hurricane storm force winds are defined as 64 knots (74 mph). The information available for the validation storms was reviewed, but only Hurricane Wilma contain information regarding the radius of hurricane force winds. On October 23, 2005 immediately prior to landfall on the west coast of Florida, Wilma’s hurricane force winds (Figure 2.3, black line “R64”) extended approximately 50 nautical miles (nm) or 57 miles from the storm’s center. NOAA’S database reported that the radius of maximum sustained winds for the validation storms ranged from 9 to 36 nm with Hurricane Wilma being the greatest. As such, a 55-mile offset to either side of NOAA’s published storm tracks was assumed for the analysis presented below to represent the segment of coastline that likely experienced the greatest storm surges during a given validation storm.

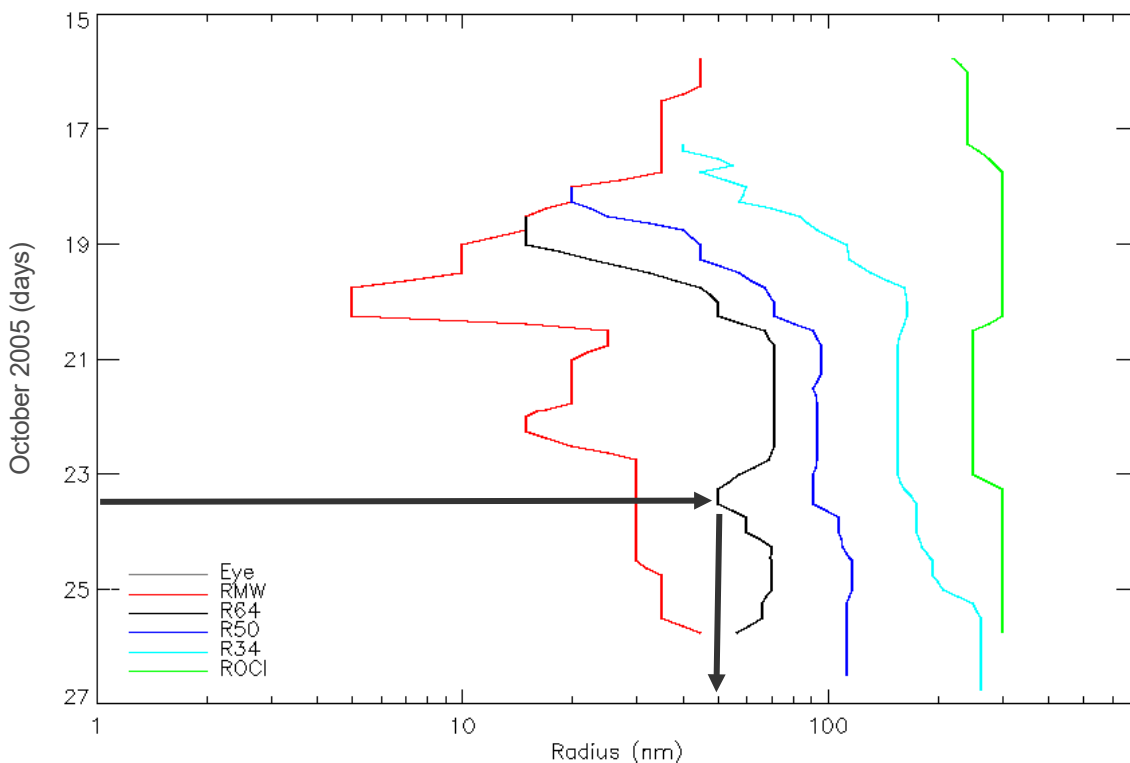


Figure 2.3: Hurricane Wilma – Wind Field Time Series [NOAA, 2020]

FEMA’s SWAN+ADCIRC model validation was based on 244 measured peak water levels (58 from hydrographs and 186 from HWM). The locations of the measured water levels used by FEMA were analyzed with respect to the 55-mile offset relative to the tracks of the validation storms. The locations of the measured water levels within the 55-mile offset (green dots) and outside the offset (red dots) for each of the validation storms are shown in Figure 2.4 through Figure 2.8. This analysis is summarized in Table 2.1 and revealed the following regarding the validation storms and measured water level locations.

- Hurricanes Betsy and David validations were based on comparisons with 5 and 4 measured water level locations, respectively. 80% (Betsy) and 50% (David) of the measurements for these storms were outside the 55-mile offset.
- Hurricanes Andrew and Wilma validations were based on 80+ comparisons of measured water level locations. 75 (94%) of the locations were within the offset for Hurricane Andrew, while 18 (21%) were within the offset for Hurricane Wilma.
- **53% (130 out of 244) of the measured water level locations used by FEMA to validate the model were within the 55-mile offset from the validation storm tracks where storm surges were more likely to be experienced; 47% were outside the offset.**

Table 2.1: Measured Water Levels Locations relative to Storm Track Offset

Validation Storm	Measured Water Level Locations		
	Within Offset ¹	Outside Offset ¹	Total
Betsy (1965)	1 (1 Hydrograph + 0 HWM)	4 (4 Hydrograph + 0 HWM)	5 (5 Hydrographs + 0 HWM)
David (1979)	2 (2 Hydrograph + 0 HWM)	2 (2 Hydrograph + 0 HWM)	4 (4 Hydrographs + 0 HWM)
Andrew (1992)	75 (6 Hydrograph + 69 HWM)	5 (5 Hydrograph + 0 HWM)	80 (11 Hydrographs + 69 HWM)
Georges (1998)	34 (2 Hydrograph + 32 HWM)	35 (16 Hydrograph + 19 HWM)	69 (18 Hydrographs + 51 HWM)
Wilma (2005)	18 (12 Hydrograph + 6 HWM)	68 (8 Hydrograph + 60 HWM)	86 (20 Hydrographs + 66 HWM)
Total:	130	114	244
Percentage:	53%	47%	100%

¹Offset = 55 miles on either side of NOAA's published storm tracks.

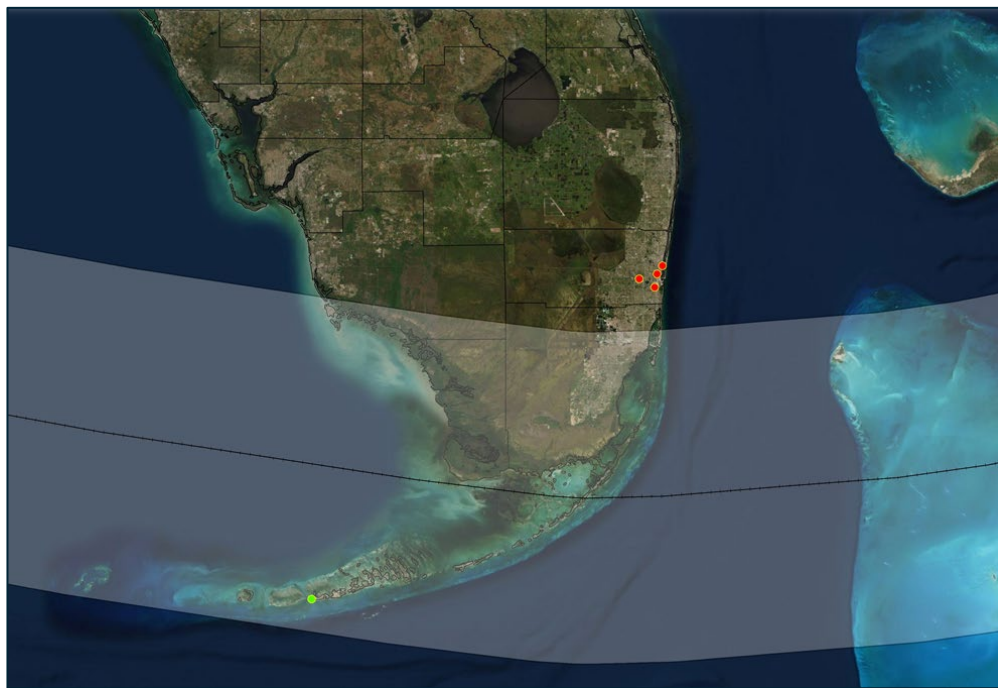


Figure 2.4: Measured Water Level Locations relative to Storm Track Offset – Hurricane Betsy

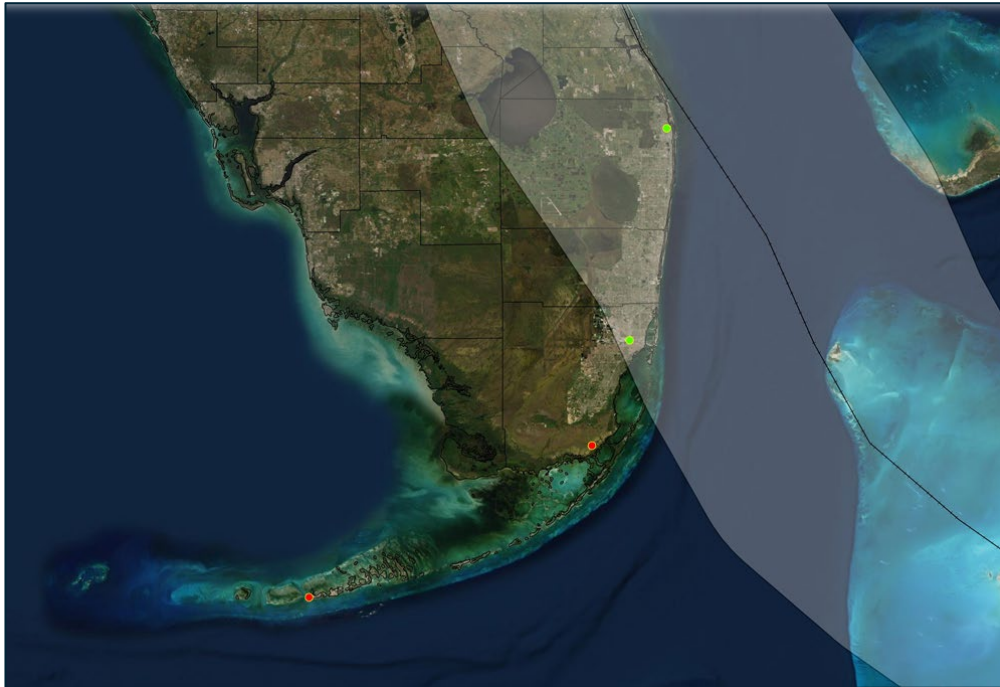


Figure 2.5: Measured Water Level Locations relative to Storm Track Offset – Hurricane David

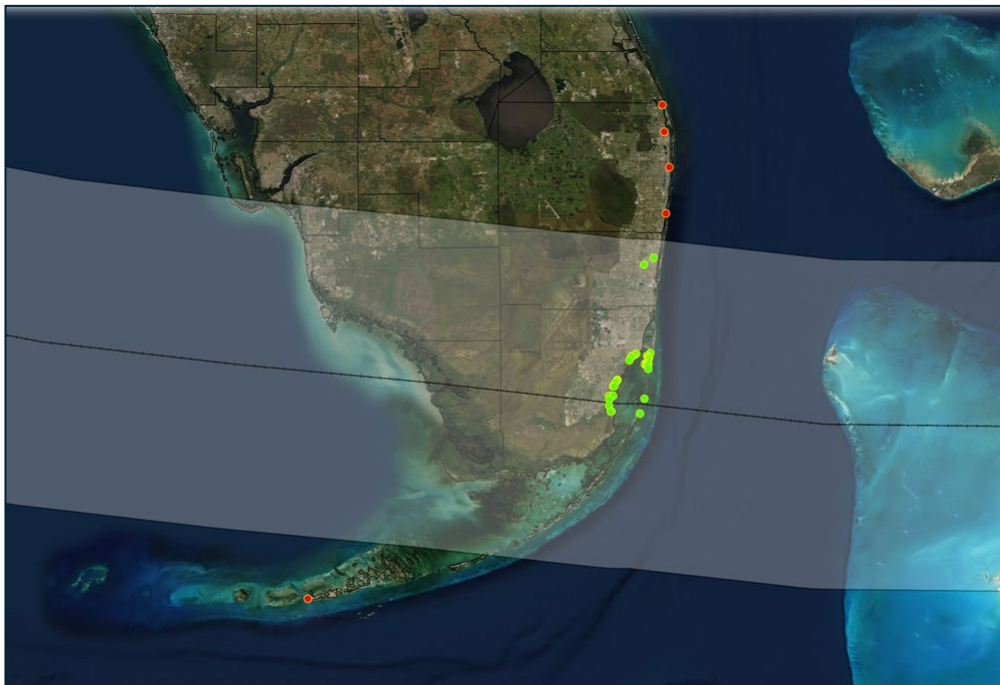


Figure 2.6: Measured Water Level Locations relative to Storm Track Offset – Hurricane Andrew

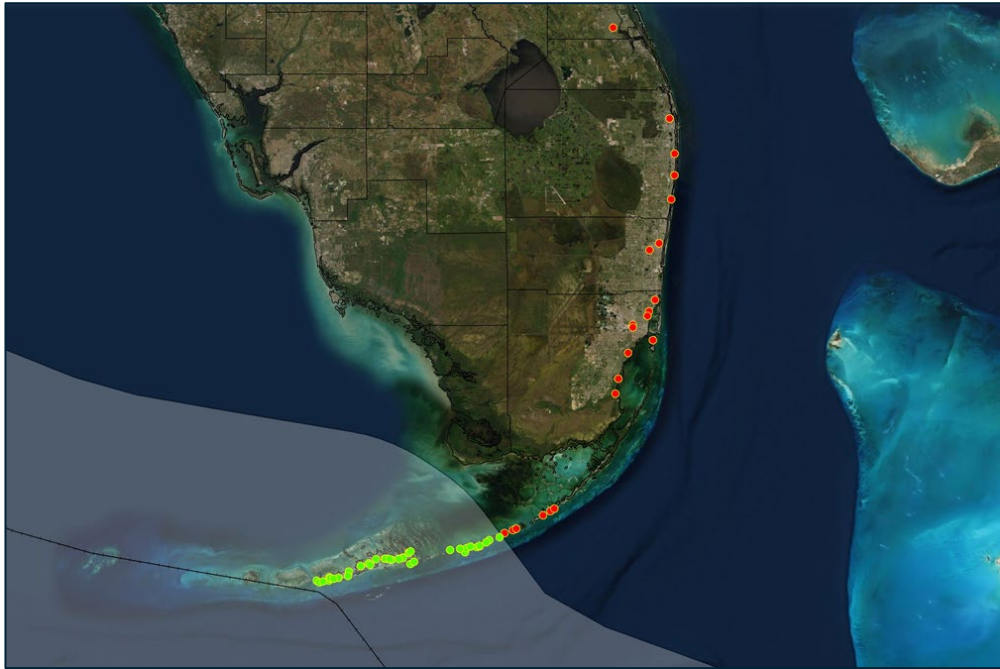


Figure 2.7: Measured Water Level Locations relative to Storm Track Offset – Hurricane Georges

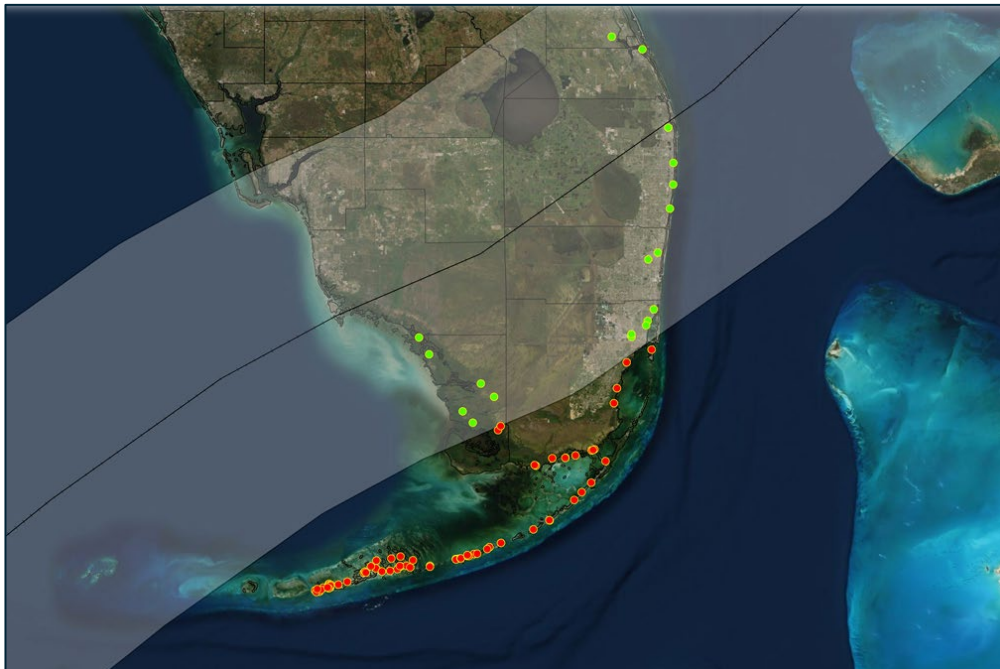


Figure 2.8: Measured Water Level Locations relative to Storm Track Offset – Hurricane Wilma

2.2 Model Uncertainty

The model uncertainty defined by FEMA is comprised of two terms: model skill; and the planetary boundary layer terms. The model skill term “represents the variations in water surface elevations due to lack of modeling accuracy as a result of approximations in physical processes” [12]. The planetary boundary layer term “represents the variations in water surface elevations due to a range of departures from the real behavior of hurricane wind and pressure fields that are not well represented by the planetary boundary layer” [12]. Model uncertainty discussed in this section pertains to the model skill term.

FEMA compared 244 measured peak water levels to modeled peak water levels to assess the SWAN+ADCIRC model’s ability to simulate the peak of the storm stage during the validation storms. The model’s ability was measured as uncertainty (skill), which was defined by FEMA as the standard deviations of the differences between model and measured water levels. FEMA identified an overall model uncertainty of 1.54 feet as shown in Table 2.2, but FEMA did not consider the proximity of measured water levels with respect to the storm tracks as part of the model validation.

Further analysis of the model uncertainty was performed with respect to the measured water level locations within and outside the 55-mile offset. (Table 2.2). The following was revealed.

- Hurricane Betsy: Model uncertainty could not be mathematically quantified within the offset, because only one location was available.
- Hurricanes Andrew and Wilma: The storms contained the greatest number of measured water level locations as compared to the other validation storms, but the storms had the greatest model uncertainties within the offset as well as for FEMA’s approach in considering all of the locations. FEMA spent considerable efforts to improve the model validation for these storms. Hurricane Wilma was considered in both the SFL and East Coast Central Florida (ECCFL) studies, but ultimately eliminated from the ECCFL model validation citing “improvement of the capability of the [model]...to reproduce non-existing storm conditions within the project area,” as well as “increased uncertainty in the wind and pressure fields for existing storms” [12]. Significant disagreement between modeled and measured water levels for Hurricane Andrew was noted by FEMA during the SFL study model validation, which necessitated an extensive sensitivity analysis of various parameters including bottom friction, nearshore reef elevations, wind sheltering and canopy settings, water depths in Biscayne Bay, initial water levels, wind drag coefficients, wind speed factors, storm landfall location, and storm forcing time intervals. The sensitivity analysis for Hurricane Andrew accounted for 75 out of the 142 model setup iterations performed by FEMA to validate the model. Ultimately, FEMA concluded that the model during Hurricane Andrew “produced a limited validation of the storm surge” [9] for the SFL study.
- **The overall model uncertainty within the offset was 1.95 feet as compared to 0.87 feet outside the offset. The model uncertainty within the offset was 2.24 times greater than the uncertainty outside the offset, which suggests that the model was not able to accurately simulate peak water levels within the areas that storm surges were most likely to be experienced.**
- The ECCFL study reported a model validation with an uncertainty of 0.75 feet for a study area with a 130 mile north-south coastline length. The model uncertainty for the SFL study within the 55-mile offset (= 110 miles of coastline for each storm) was 1.95 feet or 2.6 times greater than the ECCFL study.

Table 2.2: Model Uncertainty relative to Storm Track

Validation Storm	Model Uncertainty (feet)		
	Within Offset	Outside Offset	FEMA
Betsy (1965)	-	0.72	0.72
David (1979)	0.11	0.15	0.13
Andrew (1992)	2.05	0.58	2.00
Georges (1998)	0.99	0.94	0.99
Wilma (2005)	2.11	0.87	1.41
Overall:	1.95	0.87	1.54

The modeled versus measured peak water levels within the 55-mile offset, outside the offset, and for all points as reported by FEMA are presented as scatter plots in Figure 2.9. Clustering of points along the diagonal line in the figure indicates agreement between the modeled and measured data; greater spread indicates less agreement.

- According to NOAA’s tide gage (Station #8722670) at the Lake Worth Pier in Palm Beach County, the highest astronomical tide for the tidal epoch between 1983 and 2001 was approximately +1.8 feet, NAVD88. Measured water levels below this elevation (grey boxes) were assumed to be largely influenced by astronomical tides and below the magnitude of the 1% still water elevations (SWEL) that the SFL study targeted.
- FEMA’s modeling resulted in 1% SWEL’s ranging from 5 to 9 feet, NAVD88 within Palm Beach County (orange boxes).
- Within the 55-mile offset (left panel), there was noticeably greater spread (less agreement) between the measured and modeled data above, below, and within the range of FEMA’s 1% SWEL. Outside the 55-mile offset (middle panel), there was noticeably less spread (better agreement) but below the range of FEMA’s 1% SWEL. All of the data as presented by FEMA (right panel) was provided for reference.

The analysis presented herein demonstrates that FEMA’s ADCIRC+SWAN model had limited accuracy in simulating storm surge. This limitation contributed to greater model uncertainty and ultimately increased statistical SWEL (see Section 3).

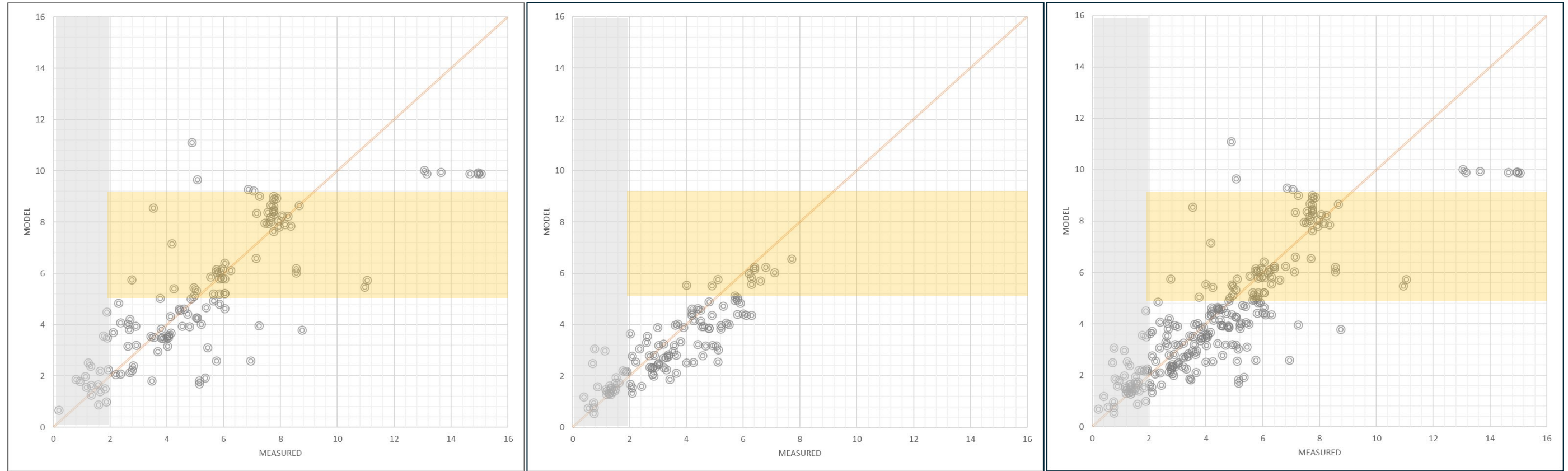


Figure 2.9: Measured-to-Modeled Peak Water Level (Left panel: Within Offset; Middle panel: Outside Offset; Right panel: FEMA/all)

2.3 Gage Selection

FEMA selected five storms for validation of the SWAN+ADCIRC model; one of which was Hurricane Wilma. Hurricane Wilma occurred in 2005 and tracked from southwest to northeast across the study area. The hurricane made landfall on the west coast within Collier County near Naples and exited on the east coast within Palm Beach County near Juno Beach. The model validation associated with Hurricane Wilma was reviewed further for the following reasons.

- It “did not produce significant surge in southern Palm Beach County or Broward Counties” [9] according to FEMA.
- It was the only “west” coast storm (i.e. making landfall on the west coast of Florida) and thus represented the only exiting storm for the SFL study.
- It had the second highest model uncertainty of the SFL study validation storms following Hurricane Andrew.
- It was the only common validation storm between FEMA’s ECCFL study and the SFL study. The ECCFL study area extended north of the SFL study area to include Martin, St. Lucie, Indian River, and Brevard Counties.
- It was ultimately eliminated from the model validation of the ECCFL study citing “improvement of the capability of the [model]...to reproduce non-existing conditions” as well as “increased uncertainty in the wind and pressure fields for existing storms.”

FEMA’s model validation was based on the difference between measured and modeled peak water levels. Two hydrograph gages presented for the ECCFL within Palm Beach County included the South Florida Water Management District’s (SFWMD) gages S46_T and S40_T positioned downstream (ocean side) of the SWFMD’s water control structures for the C-18 and C-15 canals, respectively. The modeled water levels from the SFL study and ECCFL study overlain on the measured water levels at the S46_T and S40_T gages are discussed below.

- **SFWMD Gage S46_T (Figure 2.11): The gage is located within the Loxahatchee River system where the greatest discrepancies in 1% SWEL between the ECCFL and SFL studies were identified by FEMA. The gage was located approximately 2 miles north of Wilma’s track according to NOAA, but the gage was not included in FEMA’s model validation for the SFL study despite it being considered in the ECCFL study. FEMA did not provide an explanation for excluding the gage.** The maximum WSE modeled during the ECCFL study was 1.21 feet higher than the measured water level on October 24, 2005 (black circle). **The modeled WSE from the SFL study was extracted from FEMA’s model data at the gage location and was found to resemble a sinusoidal shape associated with astronomical tides with little evidence of storm surge being simulated by the model.**
- **SFWMD Gage S40_T (Figure 2.12):** The gage is located on the west side of the intracoastal waterway at the border of Delray Beach and Boca Raton. The WSE modeled during the ECCFL study was constant before and after the storm, which indicates an error in the model setup as it did not account for tidally induced water level changes. The maximum WSE modeled during the SFL study exhibited better agreement before and after the storm and simulating storm surge (black circle).

The comparison revealed that the SFL study exhibited better agreement with measured peak WSE in southern Palm Beach County during model validation with Hurricane Wilma as compared to northern Palm Beach County. **This suggests that the SWAN+ADCIRC model’s ability to accurately simulate storm surge in northern Palm Beach County may not be reliable and further raises doubt about FEMA excluding the northern SFWMD gage (S46_T) from the SFL model validation.** This may be related to the regional grid developed by FEMA for the storm forcing parameters not covering northern Palm Beach County and the resolution of the model mesh for simulating hydrodynamics through Jupiter Inlet (see Section 3).

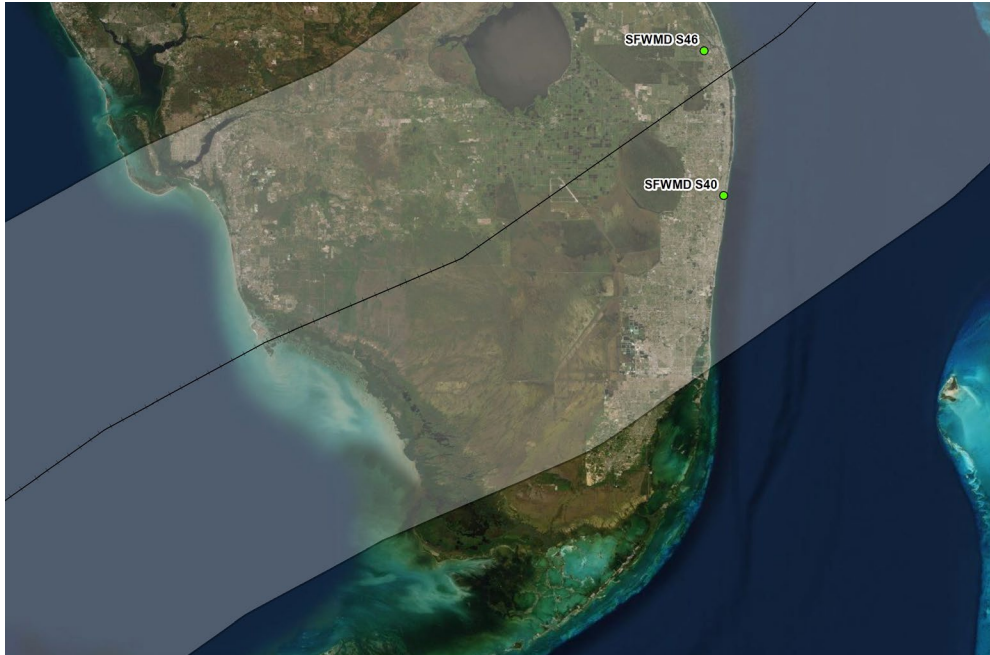


Figure 2.10: Hurricane Wilma Storm Track and SFWMD Gages

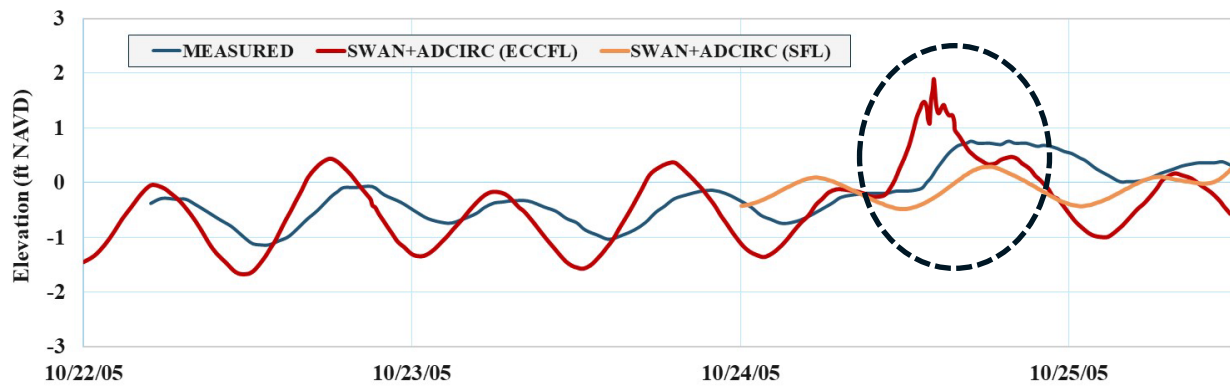


Figure 2.11: Hydrograph SFWMD Gage S46_T – Hurricane Wilma

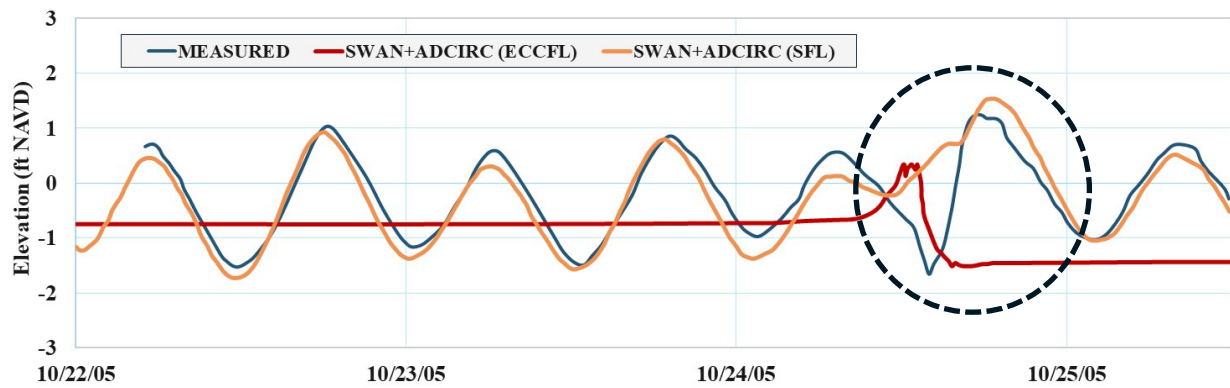


Figure 2.12: Hydrograph SFWMD Gage S40_T – Hurricane Wilma

3. Statistical SWEL

The SWAN+ADCIRC model was used by FEMA to simulate water surface elevations (WSE) throughout the study area during 392 synthetic storms. At each model node for each storm, the maximum WSE was recorded along with recurrence interval of the storm. This information along with the model uncertainty estimated by FEMA during model validation (see Section 2) were used as inputs to the SURGE_STAT program, which generated the statistical still water elevations (SWEL) for each node within the SWAN+ADCIRC model domain. A major contribution in identifying FEMA's special flood hazard areas (SFHA) is the 1% SWEL. Thus, considerations with respect to the development of the 1% SWEL are presented below.

3.1 Wind and Pressure Field Grids

In order to achieve satisfactory model performance, the SWAN+ADCIRC model requires a mesh that sufficiently represents bathymetric, topographic and land cover features of the study area as well as spatially varying storm forcing parameters (e.g. winds and pressure fields) defined on grids covering the entirety of the model domain to drive the hydrodynamic processes. FEMA states “for each new SWAN+ADCIRC model mesh, validation must demonstrate satisfactory model performance” [9]. Model performance for the SFL study focused on WSE.

The SWAN+ADCIRC model requires model mesh and grids resolution that can accurately define storm forcing parameters, resolve the hydrodynamic processes, and locally resolve numerical instabilities at land-water interfaces, around complex topographies/ bathymetries, and within inland water bodies, channels, and canals. However, running the model with finer resolutions is computationally more expensive. Computational time is balanced by creating a mesh that has coarser resolution (greater distances between nodes) outside the study area and that has finer resolution (reduced distances between nodes) within the study area, especially around features that is expected to experience high water level and current speed changes.

FEMA's coarse (basin) grid was approximately 5 times coarser than its finer (regional) grid that were used to simulate storm wind and pressure fields. FEMA's basin grid for simulating storm wind and pressure fields covers the whole model domain (Figure 3.1) at a resolution of 0.25 degrees (approximately 15 nm x 15 nm). Within the SFL study area, FEMA used a fine (regional) grid to resolve the distributions of the wind and pressure fields at a resolution of 0.05 degrees (approximately 3 nm x 3 nm) (Figure 3.2). The northern boundary of FEMA's regional grid was located approximately 12 miles north of the Palm Beach and Broward county lines, thus, **the northern 32 miles of Palm Beach County was not included in the finer regional grid and was modeled with the coarser basin grid. Therefore, the wind and pressure fields in Palm Beach County north of Boynton Inlet were modeled at a coarser resolution as compared to the rest of the SFL study area.**

The highest 1% SWEL reported by FEMA in Palm Beach County were found to occur within the southern portion of the Lake Worth Lagoon near Boynton Inlet. Review of FEMA's modeling data for the synthetic storms indicated that storm #21 produced the highest modeled WSE within this portion of the lagoon. Storm #21 was an “east” coast storm making landfall to the north near Palm Beach Inlet with a storm track from southeast to northwest as shown by the blue lines in Figure 3.1 and Figure 3.2. The track was located north, outside the regional grid. The modeled wind field at landfall for storm #21, extracted from FEMA's modeling data, is shown in Figure 3.3 to highlight the difference in model resolution between the basin (blue arrows) and regional (red arrows) grids. **The insufficient wind and pressure fields grid resolution over most of Palm Beach County limits the SWAN+ADCIRC model's ability to accurately simulate storm surges for storms making landfall north of and near the boundary of the regional grid.**

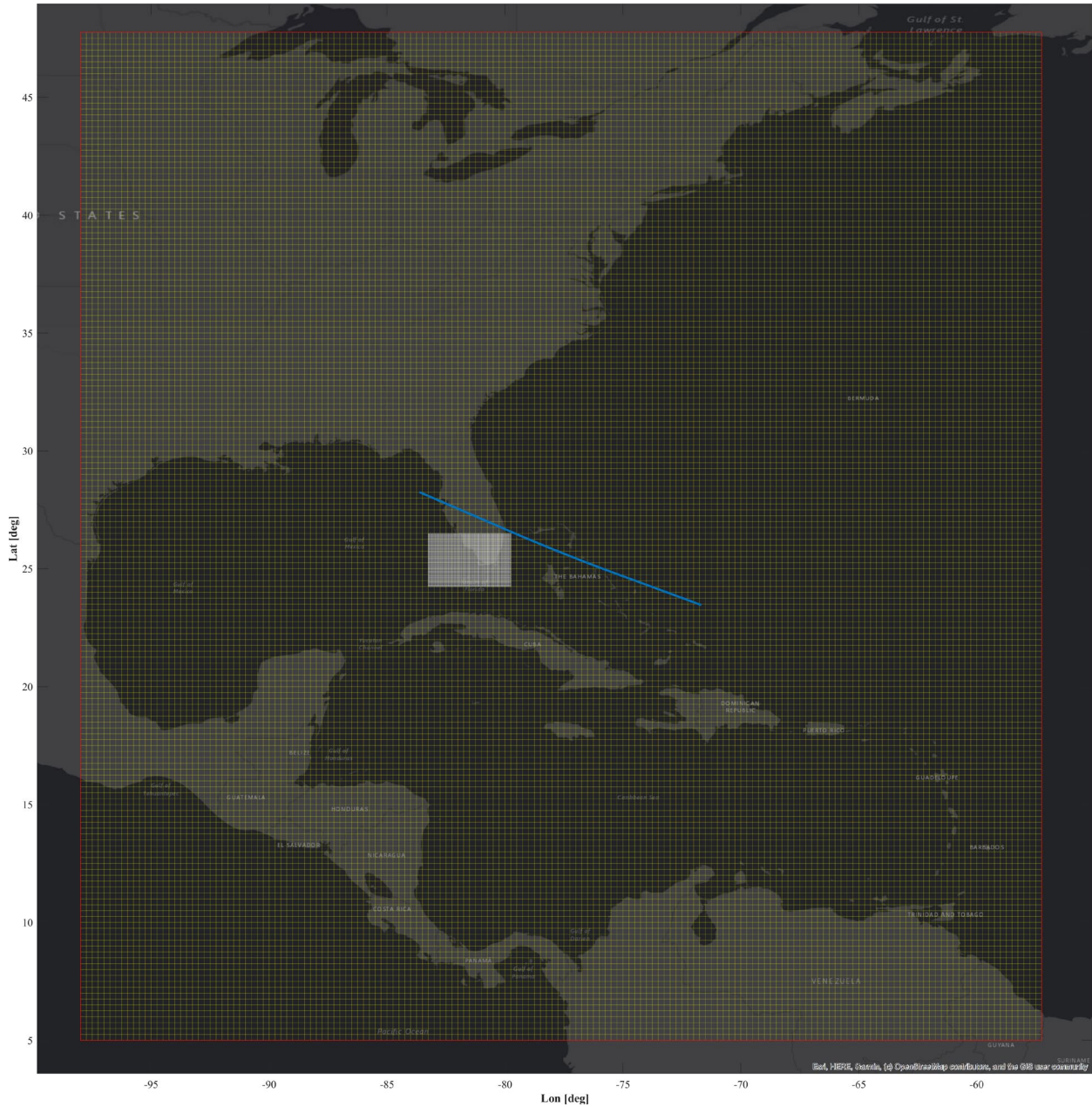


Figure 3.1: Wind and Pressure Field Grids (Basin Grid: yellow; Regional Grid: white)

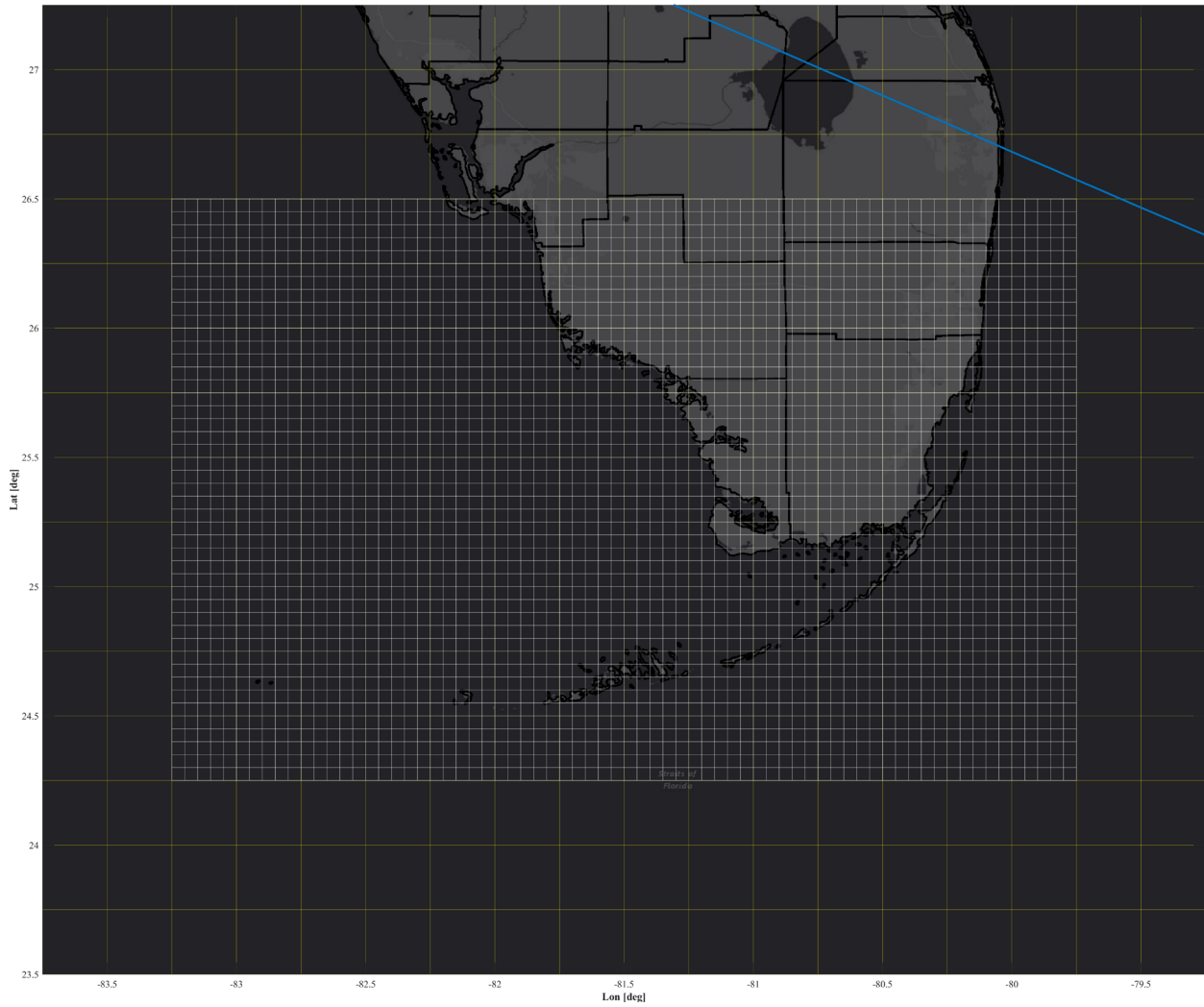


Figure 3.2: Wind and Pressure Field Grids (Basin Grid: yellow; Regional Grid: white)

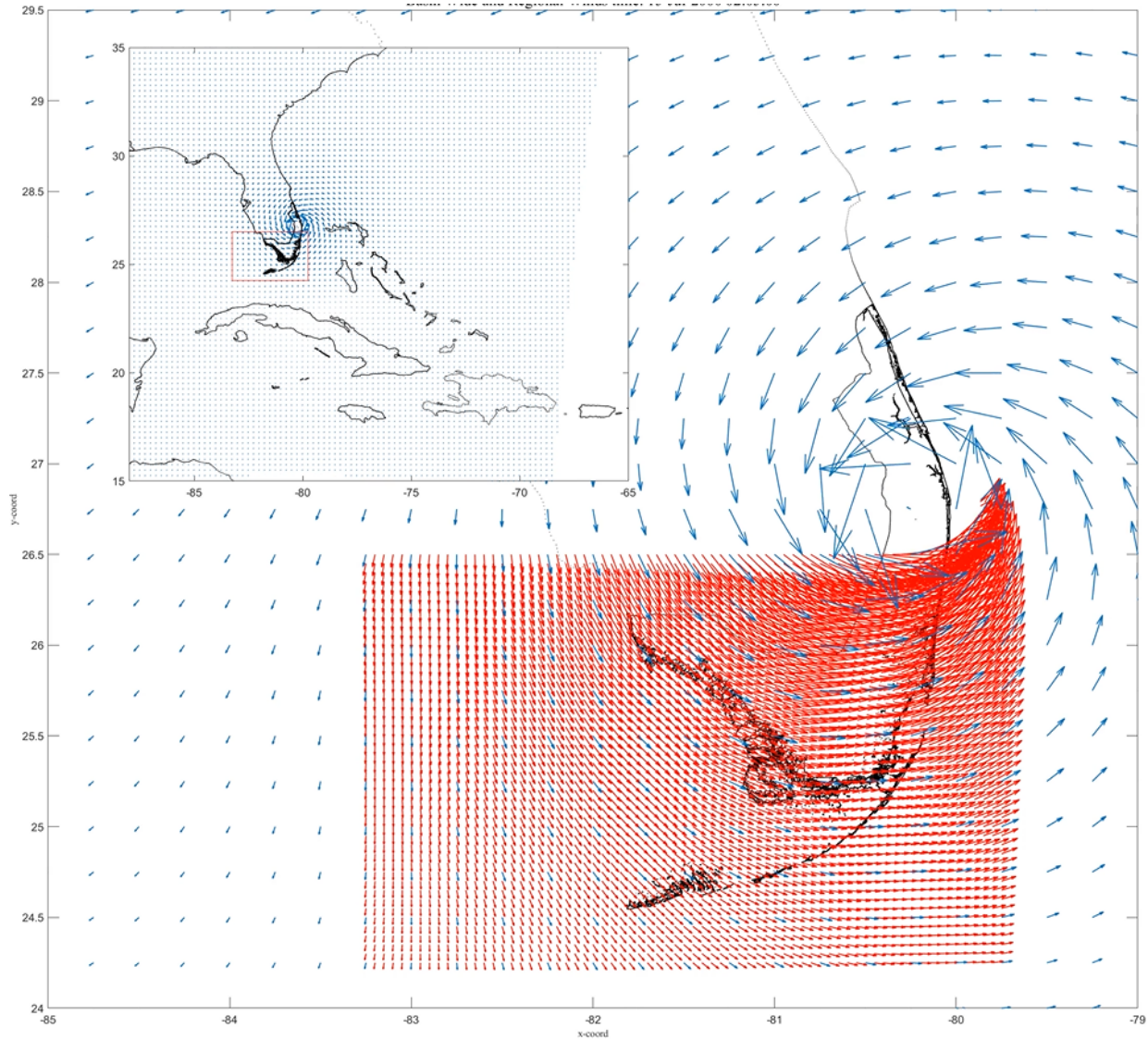


Figure 3.3: Wind Field Grids – Synthetic Storm #21 at Landfall (Basin Grid: blue; Regional Grid: red)

Storm #21, which produced the highest modeled WSE, was among 60 synthetic storms (out of FEMA’s 392 total) that made landfall outside the wind and pressure fields regional grid. Figure 3.4 show landfall locations for each of the FEMA’s 392 synthetic storms. Red dots indicate storms with landfall locations outside FEMA’s regional grid; yellow dots indicate storms making landfall within the grid. Dots located offshore of land (e.g. northern Palm Beach County, south and west of Key West) indicate the closest point of the storms’ tracks to the SFL study area.

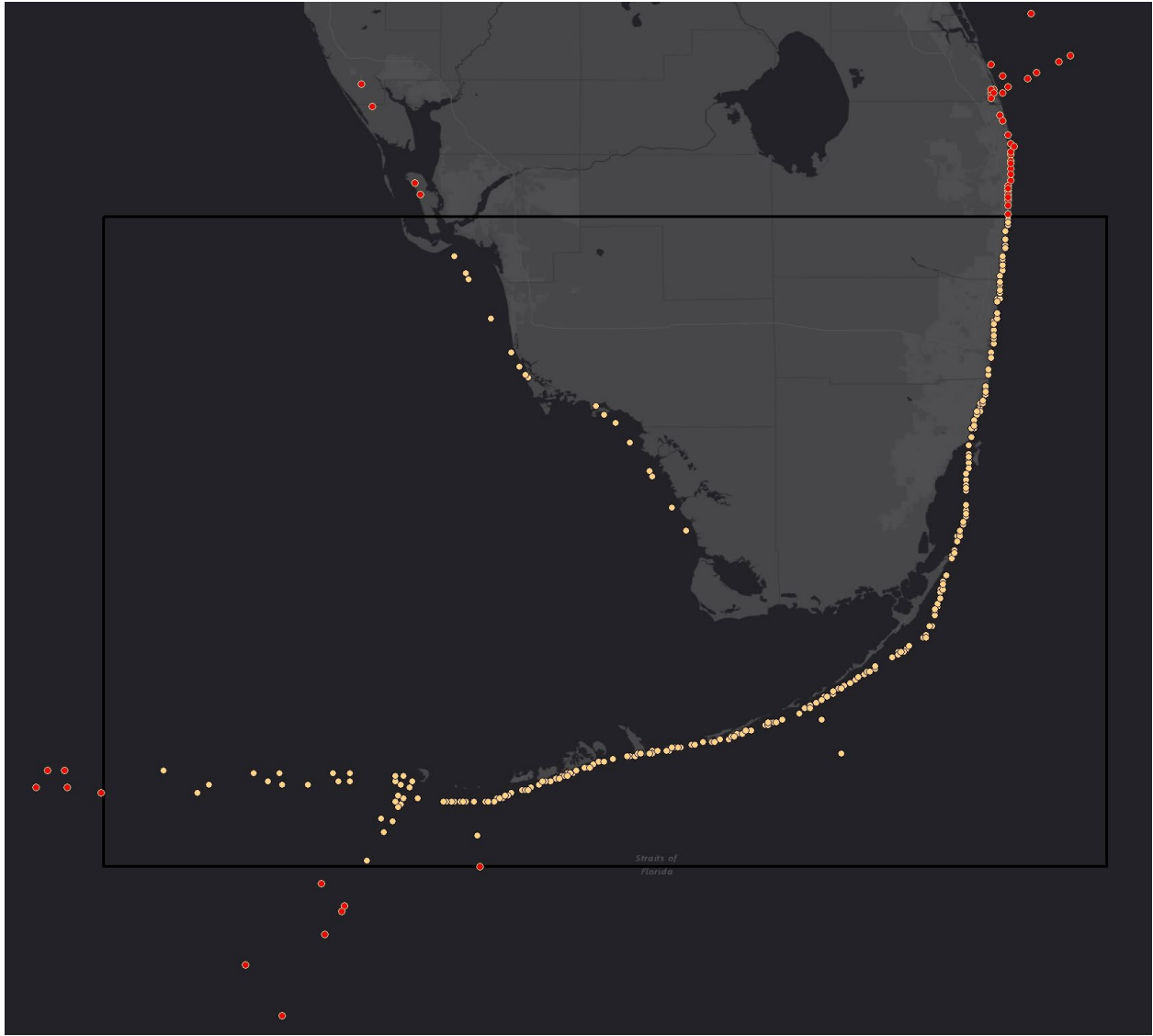


Figure 3.4: Wind and Pressure Field Regional Grid and Synthetic Storm Landfall Locations

3.2 Model Mesh

The SWAN+ADCIRC model requires a model mesh that sufficiently represents bathymetric, topographic, and land cover features within the study area. Finer mesh resolution increases computational time similar to wind and pressure field grids, but also reduces model instabilities.

FEMA encountered several model instabilities while simulating the synthetic storms. **FEMA’s approaches to resolving the instabilities were to adjust the model meshes by “filling” canals or hydraulic connections and to restrict localized water level gradients between model nodes. These approaches are routine and customary for numerical models as long as it is demonstrated that they do not alter the hydrodynamic and coastal flooding processes elsewhere within the study area. FEMA’s documentation was presented at a countywide scale, but not at a scale that the localized effects could be reviewed.**

FEMA’s approaches to resolving model instabilities were applied at the following locations within Palm Beach County:

- **“Filling” Canals:** Wetting and drying of model nodes during model simulations can cause model instabilities, which “filling” can alleviate. Canals along the Loxahatchee River and ICWW in Jupiter and Tequesta were filled by FEMA as shown in Figure 3.5. The left graphic shows the model mesh based on topographic elevations prior to “filling” canals; the right graphic shows the model mesh after “filling” canals. The red circles identify the areas that the model mesh was manipulated.
- **Restricting Localized Water Level Gradients:** Sudden and drastic changes in water levels (e.g. gradients) between model nodes can cause model instabilities, which defining localized maximum gradients can alleviate. FEMA defined gradients at two locations within Palm Beach County near the northern and southern ends of the Lake Worth Lagoon as shown in Figure 3.6. The model nodes where localized gradients were specified are indicated as by the blue and purple dots.

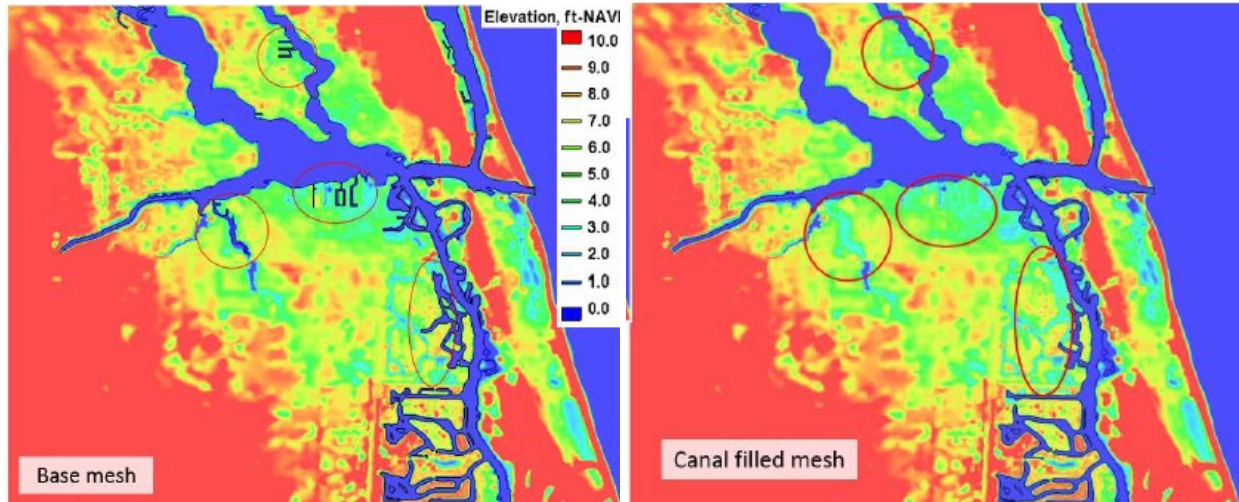


Figure 3.5: Model Instabilities – “Filled” Canals (FEMA, 2019, [9])

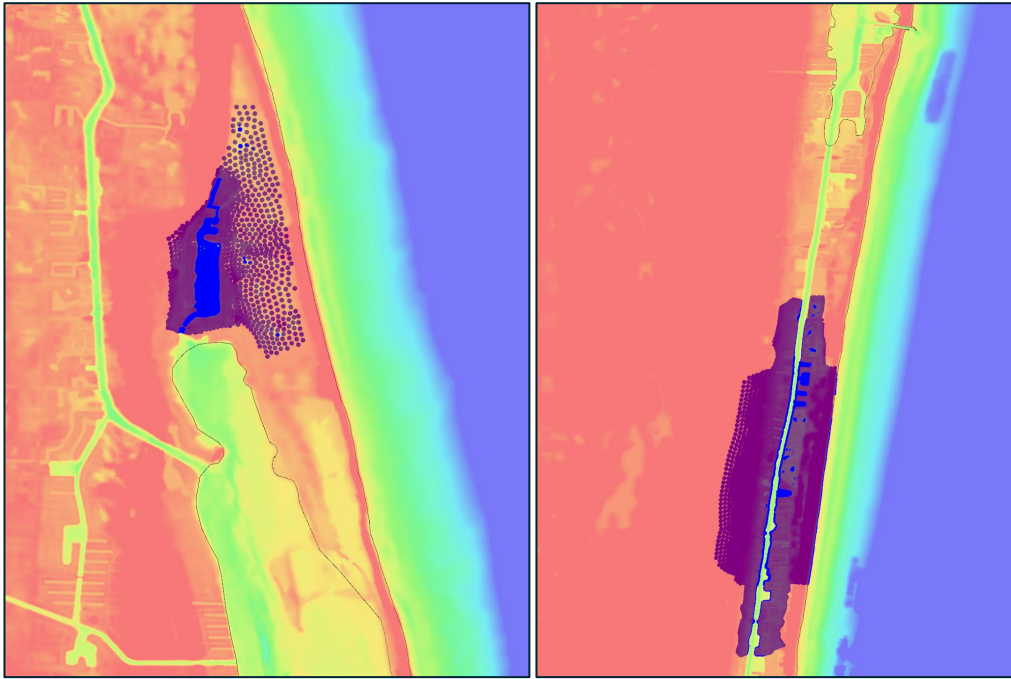


Figure 3.6: Model Instabilities – Restricted Localized Water Level Gradients (FEMA, 2019, [9])

FEMA reported that the model mesh developed for the SFL study provided sufficient resolution to “included channels at least 30-feet wide,” while channels narrower than 30 feet were excluded. **Review of FEMA’s model mesh and results of synthetic storm revealed several locations within Palm Beach County where the mesh resolution was insufficient to accurately model hydrodynamic and coastal flooding processes within the study area.** The insufficient mesh resolution and/or improper mesh definition was identified in four particular locations and are discussed below.

- Boynton Inlet:** The inlet is located at the southern end of the Lake Worth Lagoon where some of the highest modeled WSE that contributes to 1% SWEL’s within Palm Beach County were simulated by FEMA. The inlet is narrow (~120 feet wide) as compared to other east coast inlets, but 4 times wider than FEMA’s 30-foot minimum criteria. **During the synthetic storm (#21) that produced the highest WSE within the lagoon, FEMA’s model did not allow water to flow out through the inlet creating unrealistic WSE changes in the inlet thereby affecting WSE within the lagoon as the storm passed to the north.** This was evident by the elevated WSE within the lagoon (+10 ft, NAVD88), rapid drawdown of the WSE within the inlet (-10 ft, NAVD88), and then the rapid rise to match the WSE within the Atlantic Ocean (+2 ft, NAVD88) as shown by the red dashed circle in Figure 3.7. The WSE changes occurred within a distance of approximately 500 feet. A closer look at the model mesh revealed that within the inlet one node had been included along the inlet centerline with adjacent nodes along the inlet banks. The wetting/drying of nodes within the SWAN+ADCIRC model combined with insufficient mesh resolution appears to have contributed to the unrealistic WSE changes thereby not accurately simulating hydrodynamics through the inlet and in turn affecting WSE within the lagoon.

In addition, the model mesh at Boynton Inlet was found to include a gap (low section) in the north jetty at the intersection with the coastline creating an additional hydraulic connection, which does not exist.

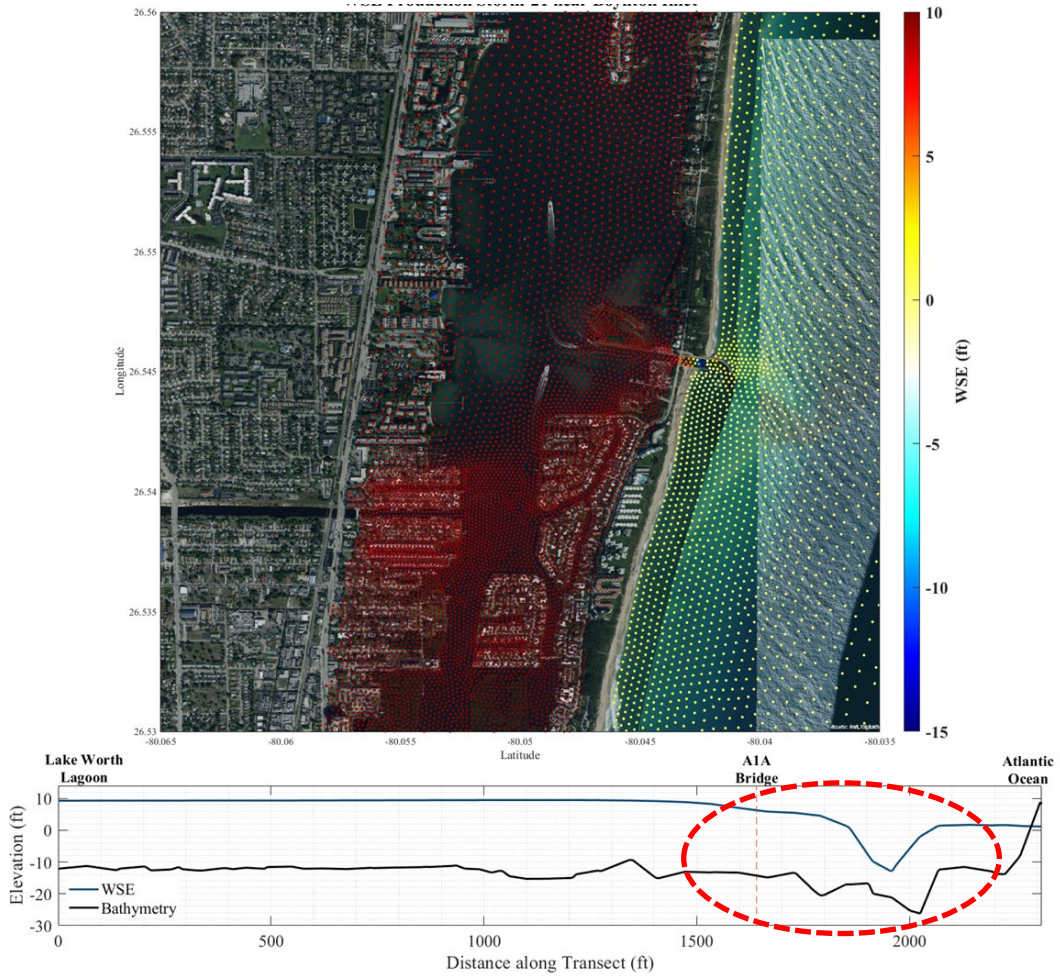


Figure 3.7: Water Surface Elevation – Boynton Inlet – Synthetic Storm #21

- Jupiter Inlet:** Similar to Boynton Inlet, discontinuities in the WSE were observed during the synthetic storm (#21) that generated the highest WSE within the inlet. As the storm passed to the south, the model did not allow water to flow into the inlet creating discontinuities in the WSE. This was evident by the elevated WSE within the Atlantic Ocean (+6 ft, NAVD88), drawdown of the WSE within the inlet (+2 ft, NAVD88), and then the rise to match the WSE within the Loxahatchee River (+4 ft, NAVD88) as shown by the red dashed circle in Figure 3.8. The discontinuities occurred within a distance of approximately 1,000 feet.

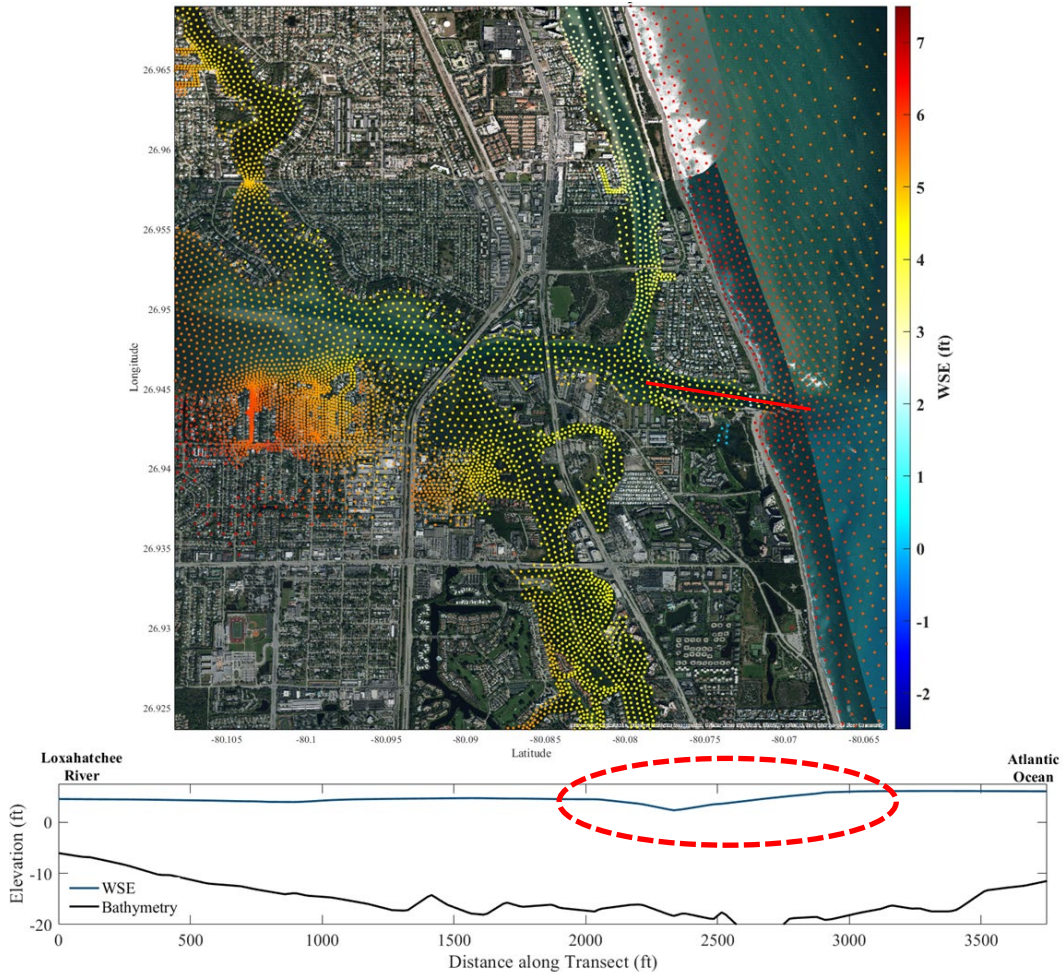


Figure 3.8: Water Surface Elevation – Jupiter Inlet – Synthetic Storm #21

- Lake Little Worth:** FEMA’s model mesh at Jack Nicklaus Drive Bridge separating Lake Little Worth from the Lake Worth Lagoon was not found to be representative of the conditions at the bridge. The mesh indicated a bottom elevation of approximately +4 feet, NAVD88 beneath the bridge, which would render the 75+ foot wide channel unnavigable to boat traffic. The model mesh created a “dike” representing a closed channel condition eliminating a known hydraulic connection greater than FEMA’s 30-foot minimum criteria. Elevated WSE within the lagoon could not flow into or out of the lake until the water overtopped the “dike” as shown by the red dashed circle in Figure 3.9. The closed condition eliminated a hydraulic connection, diverting storm surge, and thereby affecting WSE elsewhere within the localized area.

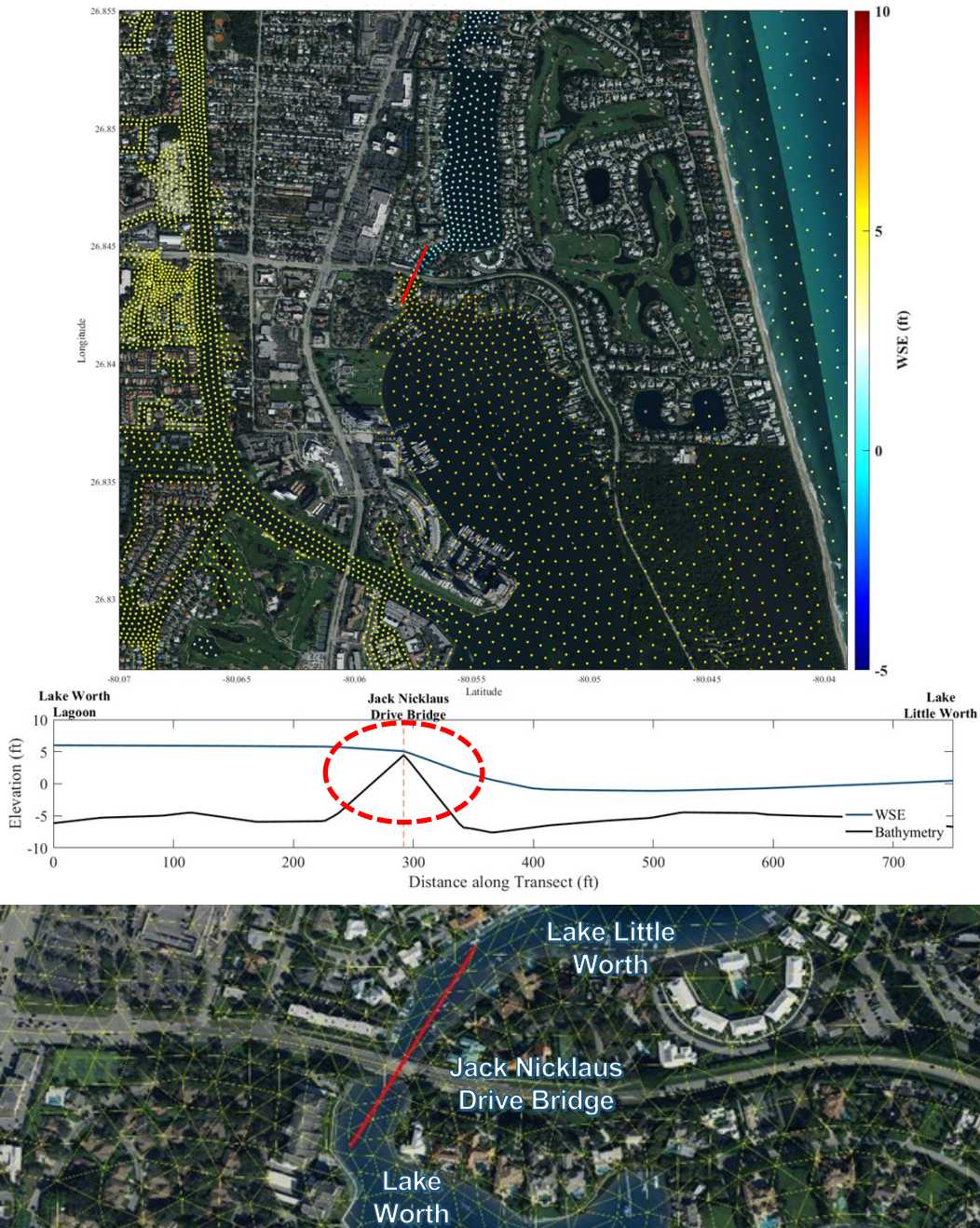


Figure 3.9: Water Surface Elevation – Lake Little Worth – Synthetic Storm #21

- Northern Palm Beach:** Similar to Lake Little Worth, the model mesh did not reflect conditions within the north-south canal under the Lighthouse Drive Bridge in Northern Palm Beach. The mesh indicated a bathymetric elevation of approximately +3 feet, NAVD88 beneath the bridge, which would render the 50+ foot wide channel unnavigable to boat traffic. The model mesh reflected closed channel condition eliminating a known hydraulic connection that is greater than FEMA's 30-foot minimum criteria. Elevated WSE north of the bridge could not flow south as shown by the red dashed circle in Figure 3.10. The closed condition eliminated a hydraulic connection thereby affecting WSE within the localized area.

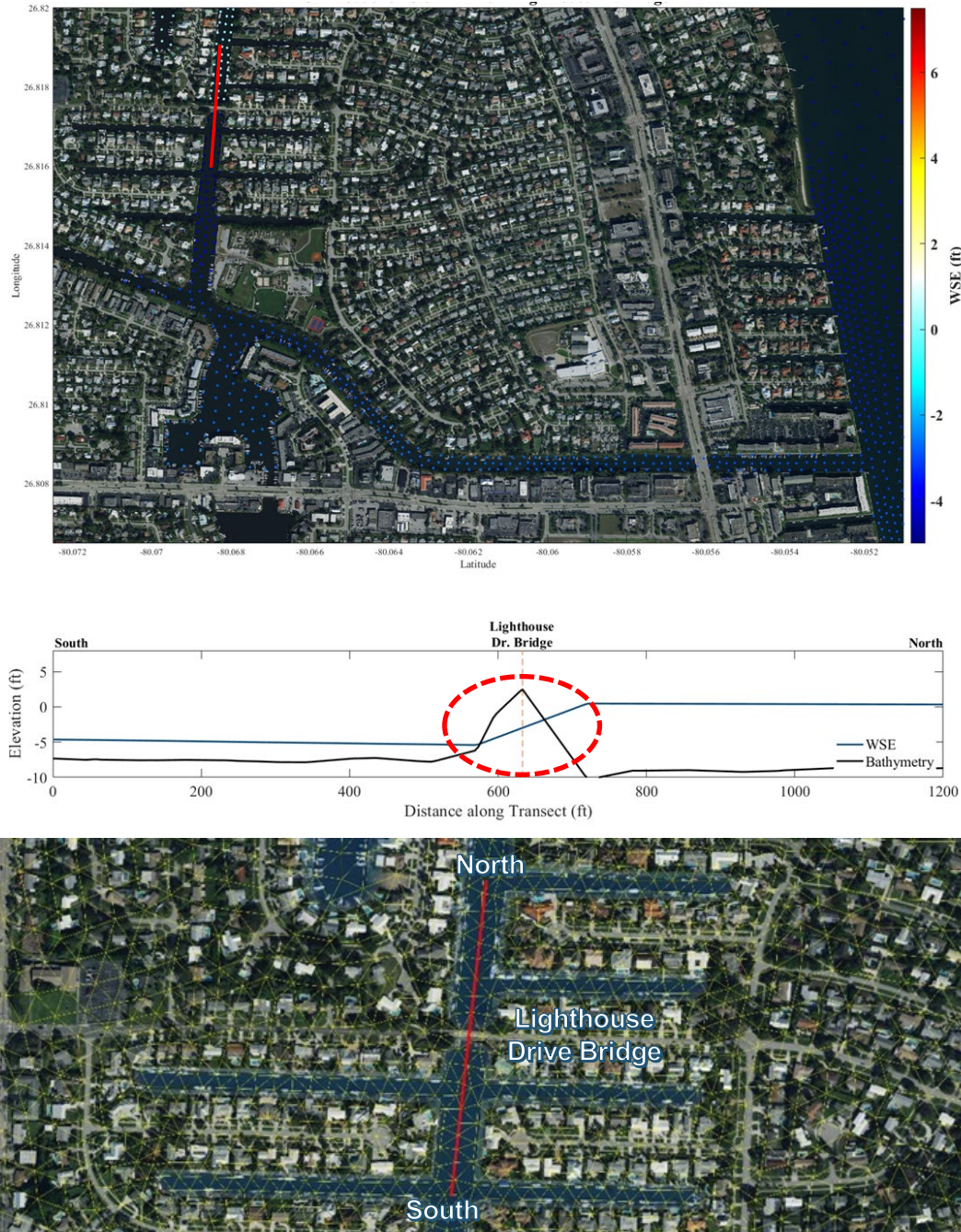


Figure 3.10: Water Surface Elevation – Northern Palm Beach – Synthetic Storm #21

3.3 1% SWEL

The 1% SWEL was considered by FEMA as the major component to define the inland extent of coastal special flood hazard areas (SFHA) when overlaid on digital elevation models (DEM). The maximum water surface elevation (WSE) for each synthetic storm from the SWAN+ADCIRC modeling was recorded by FEMA at each of the nodes within the model mesh. FEMA used the maximum WSE and model uncertainties as inputs to the SURGE_STAT program to generate return frequency curves at each model node. These frequency curves are then used to derive the 1%-annual-chance WSE (1% SWEL) at each node.

FEMA's methodology to define wave input parameters for the coastal hazard analysis requires that the synthetic storm with a maximum WSE closest to the 1% SWEL be identified as well as the nine storms with WSE above and nine storms below the 1% SWEL. The average wave conditions generated by these 19 storms bracketing the 1% SWEL are then used as wave input parameters for the coastal hazard analysis.

FEMA reported that model nodes "in some areas" of the SFL study had 1% SWEL that were not bracketed in accordance with FEMA's standards or that were above the maximum WSE generated by the synthetic storms. FEMA attributed this to the model "uncertainty and the combined storm frequency curves" used to define the 1% SWEL. FEMA's methodology to extract the wave parameters for the coastal hazard analysis was modified reducing the number of storms included in the average to allow the wave parameters to be defined. However, FEMA provided limited (if any) information regarding the locations or spatial extents of the nodes where the modified methodology was applied.

Figure 3.11, developed from FEMA's modeling data, conveys the number of synthetic storms that generated WSE greater than the 1% SWEL at each of the SWAN+ADCIRC model nodes. Red nodes indicate model nodes where none of the storms generated WSE above the 1% SWEL; green nodes indicate model nodes where more than nine storms generated WSE above the 1% SWEL.

- West Coast: Offshore of the coast, the model nodes indicated there were 9+ synthetic storms with WSE above the 1% SWEL.
- East Coast: **Offshore of the coast, the model nodes indicated there were no synthetic storms with WSE above the 1% SWEL.** A major contributor to coastal storm surge on the east coast of Florida is water from the Atlantic Ocean being forced up against the coast and into interior water bodies through coastal inlets or overtopping of the barrier islands during storm events. **With no storms bracketing FEMA's 1% SWEL immediately offshore of Palm Beach County (and the east coast of the study area), the more extreme synthetic storms were not statistically represented by FEMA's modeling and/or FEMA's 1% SWEL may have been overestimated. Unreliable offshore water levels translate into potentially unreliable water levels within interior water bodies and unreliable mapping of flood risks.**

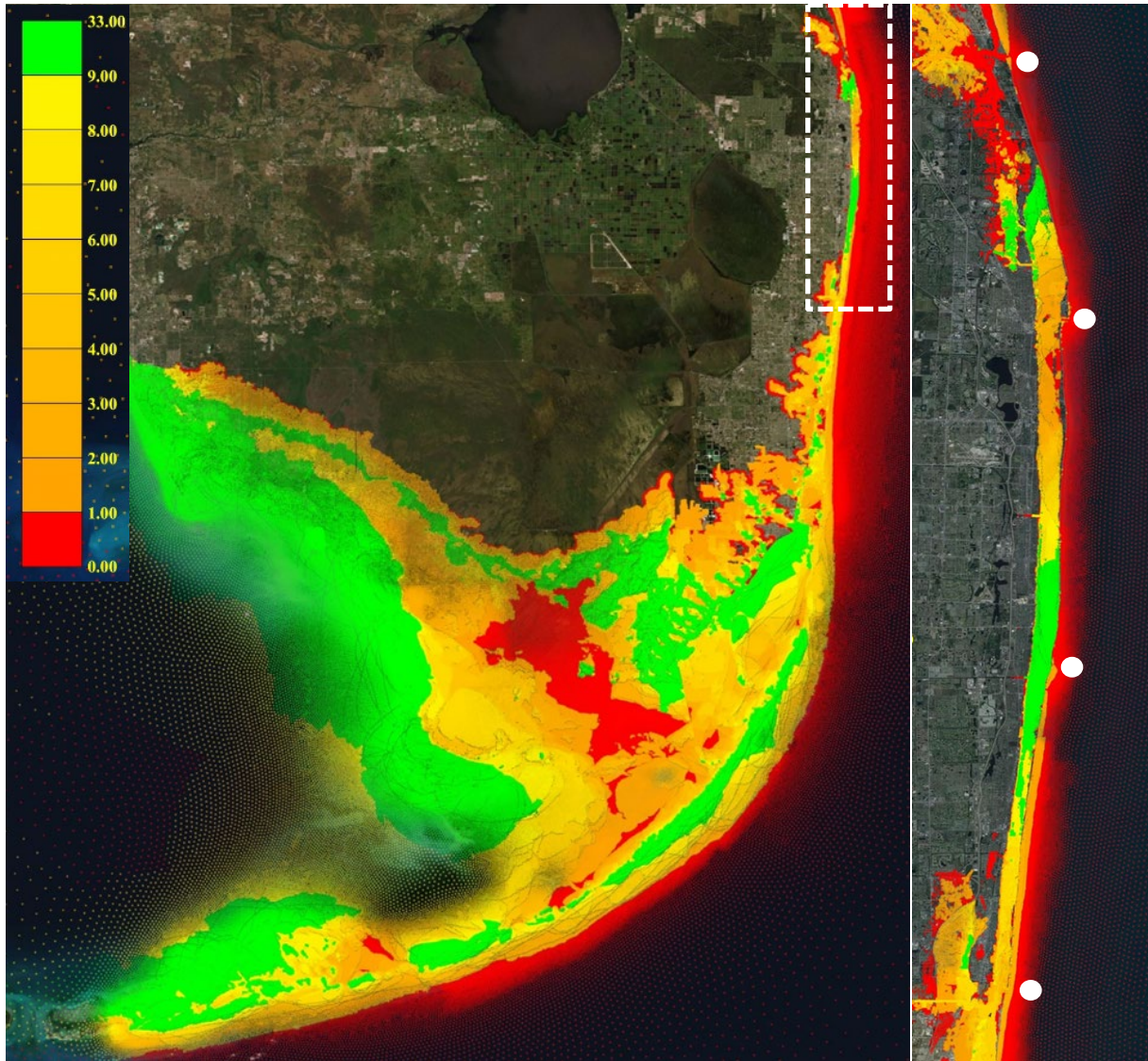


Figure 3.11: SWAN+ADCIRC Model Nodes – # of Synthetic Storms with Maximum WSE > 1% SWEL

FEMA utilized the SURGE_STAT program to generate the WSE return frequency curves at each SWAN+ADCIRC model node. The white symbols in Figure 3.11 are located offshore of the four coastal inlets in Palm Beach County, which from north to south include Jupiter Inlet, Palm Beach (Lake Worth) Inlet, Boynton (South Lake Worth) Inlet, and Boca Inlet. The symbols indicate model nodes within water depths of approximately 40-60 feet that are largely offshore of the wave breaking to be consistent with FEMA's basis for defining the starting wave conditions for its coastal hazard analysis. The WSE return period frequency curves extracted from FEMA's modeling data at each of the nodes are shown in Figure 3.12 and Figure 3.13. The curves for the "west" coast storms (red curve; exiting storms) and "east" coast storms (blue curve; landfalling storms) were shown to highlight their contribution on the "combined" curves (black) developed by FEMA. The dots along each curve represent FEMA's simulated maximum WSE for each of the synthetic storms. The horizontal green dashed line represents the threshold for defining the 1% annual chance level of occurrence (1% SWEL). In reviewing the curves, the following observations were made.

- The WSE of west coast storms were generally clustered above the 5% annual chance level. Note higher percent annual chance levels equate to lower WSE.
- The WSE of the east coast storms were above the 1% annual chance level, thus the WSE did not exceed 1% SWEL.
- The WSE of the combined set of storms (east + west coast storms) indicated even greater WSE for the 1% SWEL compared to the east and west coast storms.

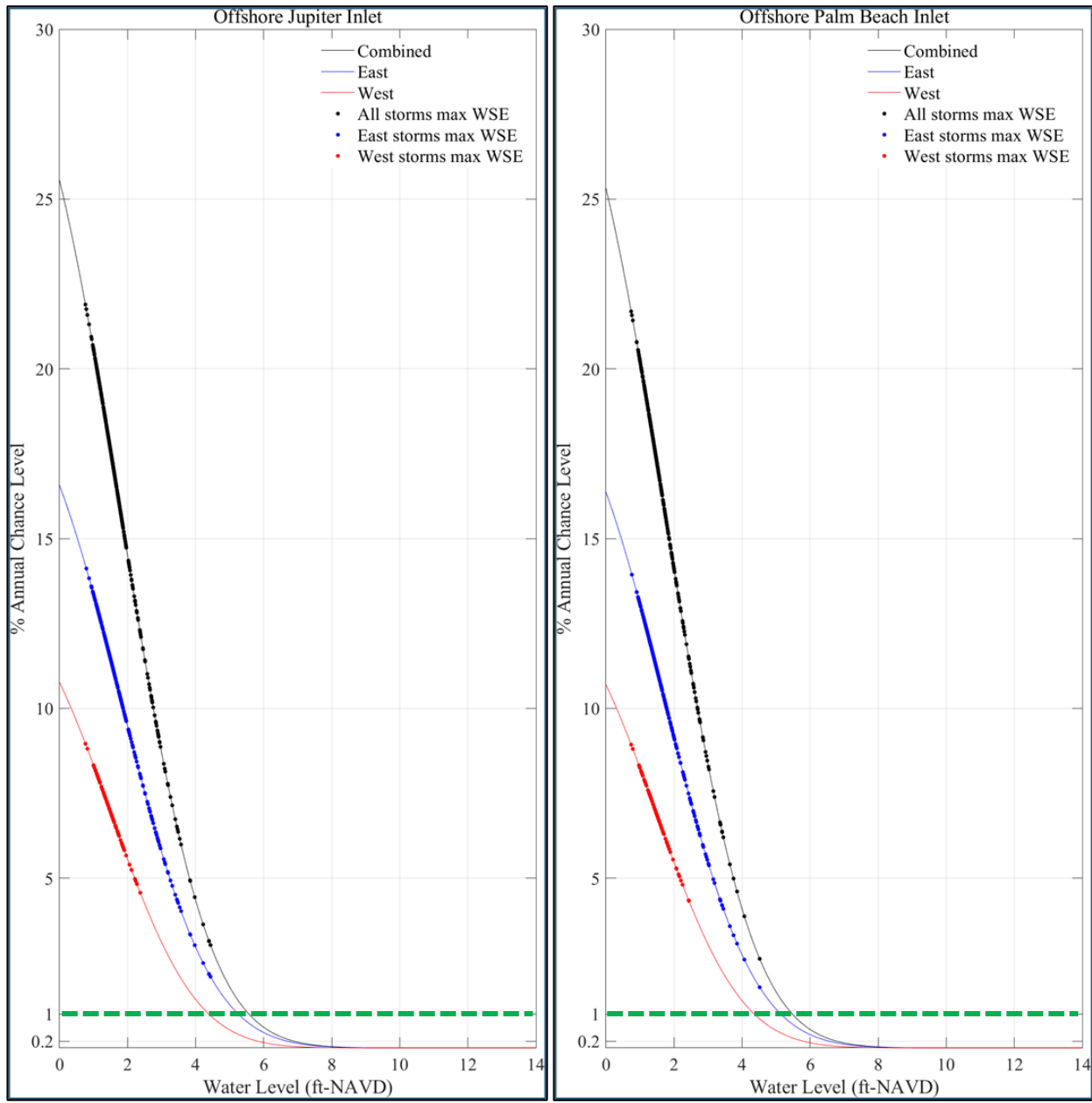


Figure 3.12: FEMA’s WSE Frequency Curve – Jupiter Inlet (left); Palm Beach Inlet (right)

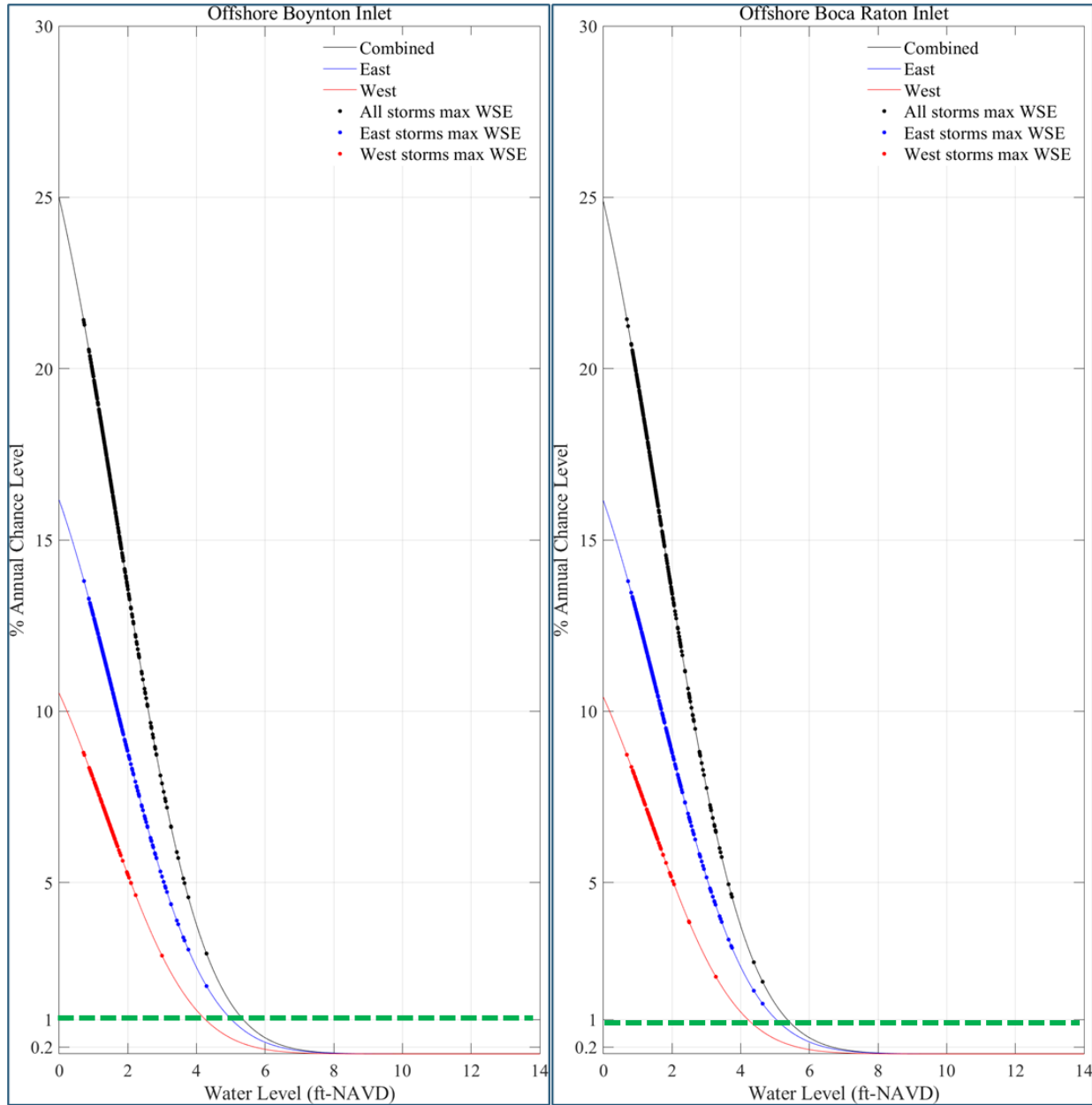


Figure 3.13: FEMA’s WSE Frequency Curve – Boynton Inlet (left); Boca Inlet (right)

The observations above highlight that the maximum WSE generated by the synthetic storms offshore of the coastal inlets in Palm Beach County were not adequate to define the “tail” end of the WSE frequency curves. The “tail” of the east and west coast curves below the 1% annual chance are the portions of the curves that when combined affect FEMA’s 1% SWEL. Furthermore, the west coast storms may not contribute to the 1% SWEL due to **the physical processes associated with exiting storms limiting the extreme WSE that can be generated within Palm Beach County**. These physical processes include the following:

- Exiting coast storms generally weaken in intensity as they pass over land; wind fields become disorganized and central pressures rise.

- The magnitude of storm surge, which is the major factor in elevated WSE, is related to a storm's time over water and the track of the storm. Exiting storms have limited time once reemerging over water to generate storm surge before moving offshore. Furthermore, the larger storm surge potential associated with a storm is generated ahead of the storm, which are directed offshore for exiting storms.

Assuming that west coast (exiting) storms were removed from the SFL study similar to the ECCFL study, the combined frequency curve would be represented by the east coast curve. **The contributions of west coast storms on the 1% SWEL offshore of Palm Beach County were approximately 0.4 feet based on FEMA's modeling data** as shown in the left panel of Figure 3.14.

Model uncertainty during the SWAN+ADCIRC model validation was also noted by FEMA as a contributing factor in the higher 1% SWEL. Model uncertainty included two terms: model skill; and the planetary boundary layer terms. The uncertainty associated with the model skill may have been closer to 1.95 feet for the SFL study as compared to 1.54 feet and 0.75 feet as reported by FEMA for the SFL study and ECCFL study, respectively (see Section 2). When the planetary boundary term (1.17 feet as reported by FEMA) was factored into the model uncertainty, the total uncertainty reported by FEMA was 1.93 feet and 1.39 feet for the SFL study and ECCFL study, respectively. Assuming that improved model validation would result in reduced model uncertainties for the SFL study that would be consistent with the ECCFL study, the contributions of increased model uncertainties on the 1% SWEL within Palm Beach County are shown in the middle panel of Figure 3.14. **The contributions of increased model uncertainty offshore of Palm Beach County were approximately 0.9 feet based on FEMA's modeling.**

The cumulative contributions of the west coast storms and increased model uncertainty offshore of Palm Beach County were estimated to have increased FEMA's 1% SWEL by approximately 1.3 feet as shown in right panel of Figure 3.14. Figure 3.15 shows the 1% SWEL as reported by FEMA (left panel) and the 1% SWEL adjusted (right panel) after removing the cumulative contributions estimated herein (middle panel). **In the absence of reperforming the modeling and given the consistent contributions offshore, a uniform downward adjustment to the 1% SWEL throughout Palm Beach County (and potentially throughout the east coast of the study area) appears most reasonable.** This contrasts with FEMA's approach of defining a transition area extending 5 miles north and 5 miles south of the Palm Beach and Martin county line within which the 1% SWEL was adjusted downward 0.85 feet within Palm Beach County and upward 0.85 feet in Martin County.

The 1% SWEL adjustments presented herein are based on modeling, information, and data provided by FEMA. Reperforming the SWAN+ADCIRC modeling is needed to more accurately assess the adjustments to consider the interdependence and spatial variability of improvements to FEMA's modeling, especially within interior water bodies hydraulically connected to coastal inlets.

Improvements to the model should include the following:

- Model validation that improves the model's ability to simulate storm surge.
- Model mesh and grids with improved resolution and accuracies.
- Re-evaluation of the storm surge bias and tidal optimization. The cumulative contributions presented herein do not include the potential contributions of 0.25 feet and 0.1 feet associated with storm surge bias and tidal optimization, respectively, as presented in Task 4.
- Assessment of the cumulative contributions and thus adjustments to the 1% SWEL within interior water bodies. The actual contributions and adjustments within these water bodies may be higher or lower than those shown given the interior water levels are directly dependent on offshore water levels.
- Outputs to FEMA's coastal hazard analysis. FEMA's analysis is dependent on the 1% SWEL and starting wave conditions to define dune response, wave runup and overtopping, and overland wave propagation. Thus, the coastal hazard analysis will be required to be updated if the 1% SWEL is adjusted.

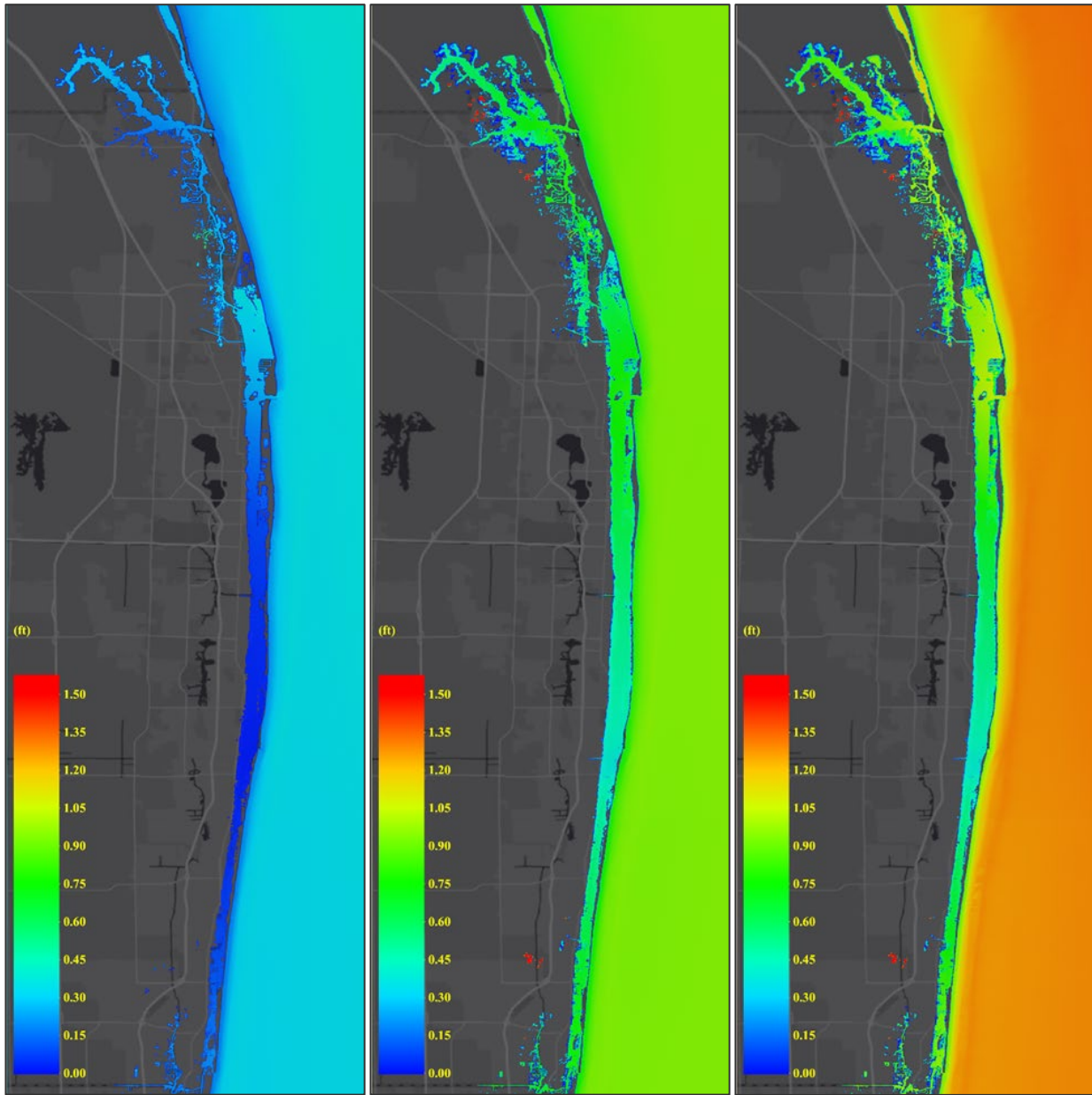


Figure 3.14: 1% SWEL Contributions: West Storms(left) +Model Uncertainty(middle) =Cumulative(right)

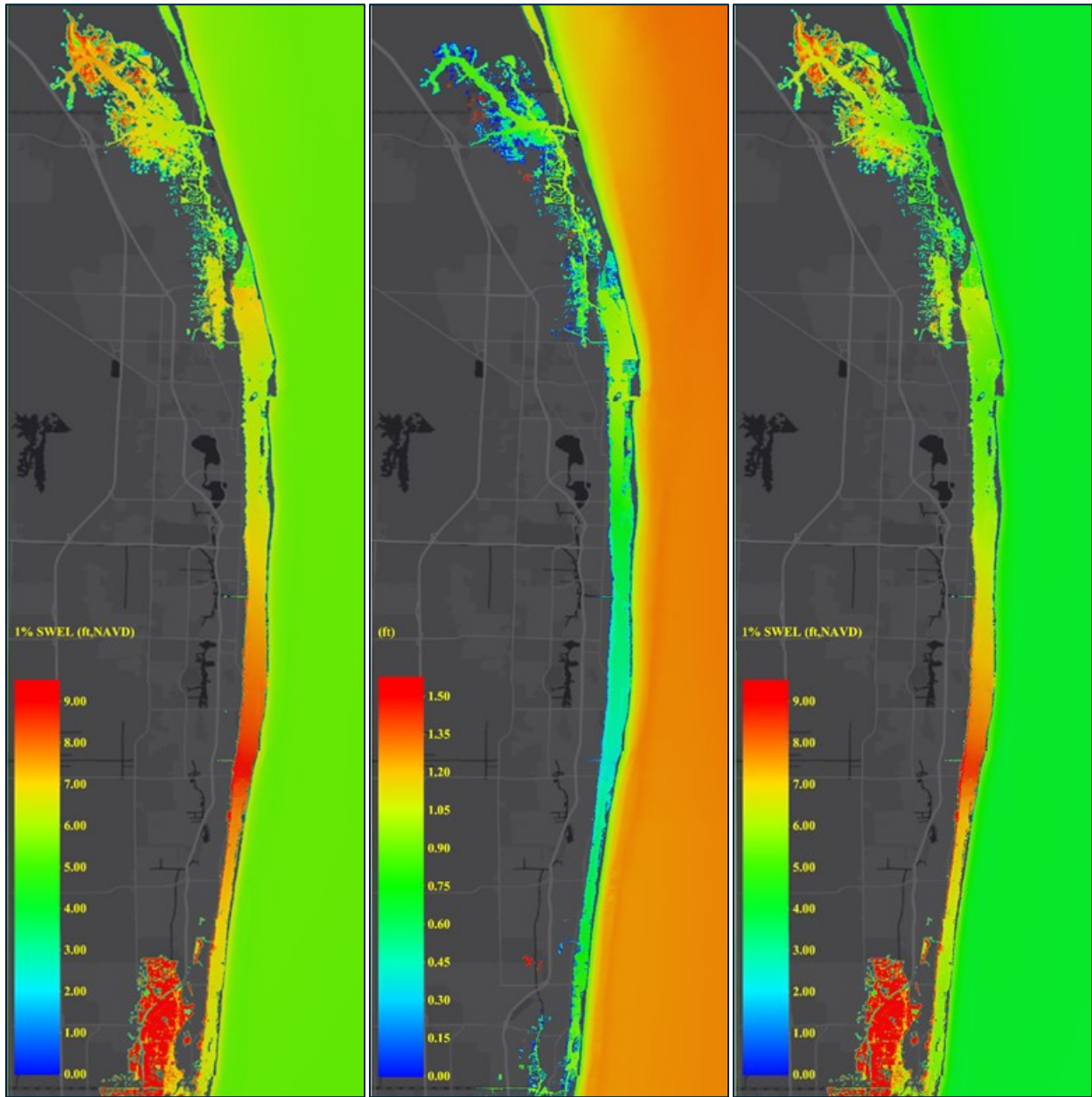


Figure 3.15: 1% SWEL: FEMA(left) – Cumulative Contributions(middle) = Adjusted(right)

4. Coastal Hazard Analysis and Mapping

4.1 Coastal Hazard Analysis

FEMA’s coastal hazard analysis along the Atlantic Coast (open coast) evaluated coastal erosion, wave runup, and overtopping during extreme storm events at defined cross-shore transects. The SFL study analyzed 170 transects within Palm Beach County for each of the coastal processes to map the VE zone.

FEMA’s VE zone is within the SFHA and is defined as “the flood insurance rate map zone that corresponds to the 1% annual chance coastal floodplains that have additional hazards associated with storm waves” [15]. The wave hazards are defined by breaking waves heights 3-feet or greater.

FEMA’s coastal erosion standard methodologies establish a dune’s response during storm events based on the volume of sand within the dune [20]. For “ridge” type dunes as shown by Figure 4.1 extracted from FEMA’s guidance document, the frontal dune reservoir is defined by the dune’s volume seaward of the dune peak and above the total stillwater elevation (1% SWEL). For “mound” type dunes, the reservoir is defined by the dune’s rear shoulder. Both types of dunes are present in Palm Beach County. A dune reservoir greater than 540 ft² results in dune retreat (erosion of the frontal dune reservoir), while volumes less than or equal to 540 ft² results in dune removal (lowering of the peak and loss of the dune feature).

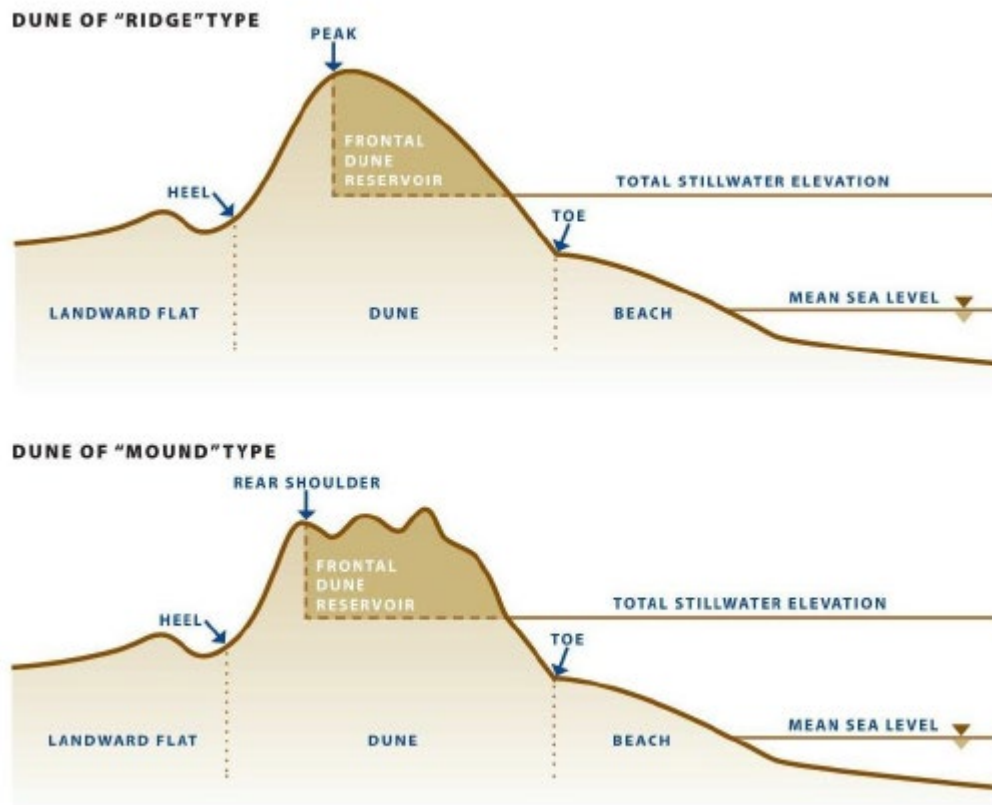


Figure 4.1: FEMA Dune Response (FEMA, 2018, [20])

Of the 170 open coast transects, breaking wave heights were used by FEMA to define the VE zone at two transects (137 and 138 at MacArthur Beach State Park). FEMA’s analysis resulted in dune removal being identified at the transects and the eroded dune profiles being specified at elevations below the 1% SWEL (see Task 4). This triggered FEMA to use breaking wave heights to define the VE zone for these transects and resulted in FEMA mapping the VE zone landward of the dune and within the Lake Worth Lagoon. As such, FEMA’s model data for the transects were reviewed with respect to the volumes of the dune reservoir and subsequent the dune responses (Table 4.1).

- **Transect 137:** FEMA’s SFL study defined the 1% SWEL at +6.36 ft, NAVD88 and the dune peak at 20.4 ft, NAVD88 which resulted in a reservoir volume of 536 ft². This was less than 540 ft² and resulted in dune removal being identified by FEMA. Inspection of the data indicated that the dune peak had been incorrectly identified along the seaward slope of the dune and that the dune peak was actually at 20.9 ft, NAVD88. If the correct dune peak had been used by FEMA (red text), the reservoir volume would have been 553 ft² and consequently a dune retreat response (not dune removal) identified by FEMA. The analysis was repeated with the 1% SWEL lowered 1.3 feet to highlight the contributions of the west coast storms and increased model uncertainty on FEMA’s coastal analysis. The lower SWEL reaffirmed a dune retreat response.
- **Transect 138:** The coastal erosion analysis was repeated with the 1% SWEL lowered 1.3 feet to highlight the contributions of the west coast storms and increased model uncertainty on FEMA’s analysis. The lower SWEL resulted in a dune retreat response as opposed to removal as identified by FEMA.

A dune retreat response at these two profiles would reduce the exposure of the northern Lake Worth Lagoon to Atlantic waves during the 1%-annual-chance event, the inland extent of the VE zone, and in turn may reduce base flood elevations (BFE) of SFHA zones mapped on FEMA’s FIRM panels within the lagoon.

Table 4.1: Dune Response

Transect (Open Coast)	FEMA SFL Study				SWEL Adjusted (-1.3 ft)		
	1% SWEL (ft, NAVD88)	Dune Peak (ft, NAVD88)	Reservoir ¹ (ft ²)	Dune Response	1% SWEL (ft, NAVD88)	Reservoir ¹ (ft ²)	Dune Response
137	6.36	20.4	536	Removal	5.06	746	Retreat
		20.9	553	Retreat			
138	6.22	22.2	430	Removal	4.92	544	Retreat

¹Dune reservoir defined by FEMA as the volume of sand seaward of the dune peak and above the 1% SWEL. FEMA specifies dune retreat when the volume greater than 540 ft² and dune removal when the volume is less.

4.2 Mapping

The SFWMD operates several water control structures in Palm Beach County, which are listed from north to south in Table 4.2.

According to FEMA, the SWAN+ADCIRC model mesh developed for the SFL study...

- "...captures the SFWMD canals from the ocean to the most seaward control structure...Upstream from the first (seaward) control structures, canal water levels can vary depending on operations at upstream and downstream control structures..."
- "...actively excludes the upstream canal by placing model nodes along the channel banks..."
- "...often the 2- and 1-percent-annual-chance water levels upstream of the structures were not calculated..."

FIRM panels to be updated for the SFL study were excluded west of the control structures at the S-44 and S-155 structures, while panels west of the S-41 and S-40 structures were included. The SFL study was performed to update flood risks associated with coastal storm surge and did not include precipitation or riverine flooding analyses. Delineations of the AE zones and BFEs upstream of the structures did not change on the preliminary FIRM’s issued for the SFL study, but X zones were mapped in greater detail. Furthermore, panels noted by “*” indicate panels where the AE zones were extended west along drainage canals for which no justification was provided by FEMA. **Updates by FEMA to SFHA mapping on the following eight FIRM panels upstream of SFWMD water control structures as part of the SFL study do not appear consistent or warranted based on the methodologies applied and justification provided by FEMA elsewhere within Palm Beach County.**

- 0778G*
- 0779G*
- 0786G*
- 0787G*
- 0788G
- 0789G
- 0976G*
- 0978G*

Table 4.2: SFWMD Water Control Structures – Palm Beach County

Water Control Structure	Canal	Bypass Elevation ¹ (ft, NAVD88)	Upstream FIRM Designation	
			Effective 2017	Preliminary ²
S-46	C-18	18.5	-	-
S-44	C-17	10.5	AE10	AE10
S-155	C-51	8.0	AE10.4	AE10.4
S-41	C-16	10.0	AE9	AE9
S-40	C-15	10.0	AE9	AE9
G-56	Hillsboro	10.4	AE	AE

¹Elevation reported by FEMA at which flood waters will bypass and flow around the structure [3].

²Released with the preliminary documents for SFL study.

FEMA’s AE zone is within the SFHA and is defined as “the flood insurance rate map zone that corresponds to the 1% annual chance coastal floodplains” [15]. FEMA’s X zone is outside the SFHA and is defined as “areas of 0.2% annual chance flood hazards and areas of 1% annual chance flood hazards with average depths of less than 1 foot or with drainage areas less than 1 square mile” [15].

5. Conclusions

FEMA's SFL study leveraged numerical modeling and analyses to better define the coastal flood risks associated with storm surge. The discussion above was intended to identify specific elements to improve the accuracy, consistency, reliability, and repeatability of the study with respect to Palm Beach County. The major elements are summarized below. Task 5 and the conclusion presented herein are intended to compliment Task 4 of Baird's technical review.

SWAN+ADCIRC Model Validation

- While it is acknowledged that FEMA's extensive model validation resulted in reasonable agreement with measured astronomical tides, less favorable agreement with measured water levels during the modeled validation storms suggests that the coastal processes and WSE associated with storm surge may not be represented by the SWAN+ADCIRC model developed by FEMA.
- FEMA's SWAN+ADCIRC model validation was based on 244 measured peak water levels. Only 53% of the measured water level locations used by FEMA to validate the model were within a 55-mile offset of the validation storm tracks where storm surges were more likely to be experienced.
- The model uncertainty within the 55-mile offset was 1.95 feet as compared to 0.87 feet outside the offset. This equated to a model uncertainty within the offset that was 2.24 times greater than the uncertainty outside the offset, which suggests that the model was not able to accurately simulate peak water levels within the areas that storm surges were most likely to be experienced.
- The SFWMD S46_T gage is located within the Loxahatchee River system where the greatest discrepancies in 1% SWEL between the ECCFL and SFL studies were identified by FEMA. The gage was located approximately 2 miles north of Wilma's track according to NOAA, but the gage was not included in FEMA's model validation for the SFL study despite it being considered in the ECCFL study. FEMA did not provide an explanation for excluding the S46_T gage from the SFL study. The modeled WSE from the SFL study was extracted from FEMA's model data at the gage location and was found to resemble a sinusoidal shape associated with astronomical tides with little evidence of storm surge being simulated by the model. Comparison with SFWMD S40_T gage in southern Palm Beach County indicated that FEMA's SWAN+ADCIRC model better simulated storm surge experienced during the storm. This suggests that the model's ability to accurately simulate storm surges in northern Palm Beach County may not be reliable and further raises doubt about FEMA excluding the northern SFWMD gage (S46_T) from the SFL model validation.

Statistical SWEL

- FEMA's regional grid developed to resolve the distributions of the wind and pressure fields did not include the northern 32 miles of Palm Beach County. Therefore, the wind and pressure fields in Palm Beach County north of Boynton Inlet were modeled at a coarser resolution as compared to the rest of the SFL study area. The insufficient wind and pressure fields grid resolution over most of Palm Beach County limits the SWAN+ADCIRC model's ability to accurately simulate storm surges for storms making landfall north of and near the boundary of the regional grid.
- FEMA's approaches to resolving model instabilities were to adjust the model meshes by "filling" canals or hydraulic connections and to restrict localized water level gradients between model nodes. These approaches are routine and customary for numerical models as long as it is demonstrated that they do not alter the hydrodynamic and coastal flooding processes elsewhere within the study area. FEMA's documentation was presented at a countywide scale, but not at a scale that the localized effects could be reviewed.
- Review of FEMA's model mesh and modeling of synthetic storms revealed several locations within Palm Beach County where the mesh resolution was insufficient to accurately model hydrodynamic and coastal

flooding processes within the study area. For example, during the synthetic storm (#21) that produced the highest WSE within the Lake Worth Lagoon, FEMA's model did not allow water to flow out through Boynton Inlet creating unrealistic WSE changes in the inlet thereby affecting WSE within the lagoon as the storm passed to the north. Other noted locations include Jupiter Inlet, Jack Nicklaus Drive bridge at Lake Little Worth, and the canal under Lighthouse Drive bridge in North Palm Beach.

- Offshore of the study area's east coast, the SWAN+ADCIRC model nodes indicated there were no synthetic storms with WSE above the 1% SWEL. With no storms bracketing FEMA's 1% SWEL immediately offshore of Palm Beach County (and the east coast of the study area), the more extreme synthetic storms were not statistically represented by FEMA's modeling and/or FEMA's 1% SWEL may have been overestimated. Unreliable offshore water levels translate into potentially unreliable water levels within interior water bodies and unreliable mapping of flood risks.
- The physical processes associated with exiting (west coast) storms may limit the extreme WSE that can be generated offshore of Palm Beach County and the contribution of these storms to FEMA's 1% SWEL. The contributions of west coast storms to the 1% SWEL offshore of Palm Beach County were approximately 0.4 feet based on FEMA's modeling data.
- Assuming that improved model validation would result in reduced model uncertainties for the SFL study that would be consistent with the ECCFL study, the contributions of increased model uncertainties to the 1% SWEL offshore of Palm Beach County were approximately 0.9 feet based on FEMA's modeling data.
- The cumulative contributions (adjustments) of the west coast storms and increased model uncertainty offshore of Palm Beach County were estimated to have increased FEMA's 1% SWEL by approximately 1.3 feet. In the absence of reperforming the modeling and given the consistent contributions offshore, a uniform downward adjustment to the 1% SWEL throughout Palm Beach County (and potentially throughout the east coast of the study area) appears most reasonable. This contrasts with FEMA's approach of defining a transition area extending 5 miles north and 5 miles south of the Palm Beach and Martin county line within which the 1% SWEL was adjusted downward 0.85 feet within Palm Beach County and upward 0.85 feet in Martin County.
- The 1% SWEL adjustments presented herein are based on modeling, information, and data provided by FEMA. Reperforming the SWAN+ADCIRC modeling is need to more accurately assess the adjustments to consider the interdependence and spatial variability of improvements to FEMA's modeling, especially within interior water bodies hydraulically connected to coastal inlets.

Coastal Hazard Analysis and Mapping

- Of the 170 open coast transects, breaking wave heights were used by FEMA to define the VE zone at only two transects (137 and 138 at MacArthur Beach State Park). A 1.3-foot downward adjustment to the 1% SWEL, as quantified above, would impact the coastal erosion analysis and would have resulted in a dune retreat response instead of dune removal as identified by FEMA at the two transects for the northern Lake Worth Lagoon. A dune retreat response at these transects would reduce the exposure of the lagoon to Atlantic waves during the 1%-annual-chance event, the inland extent of the VE zone, and in turn may reduce base flood elevations (BFE) of SFHA zones mapped on FEMA's FIRM panels within the lagoon.
- According to FEMA, the SWAN+ADCIRC model mesh developed for the SFL study excludes canals upstream of SFWMD water control structures and 1% SWELs were not calculated. Updates by FEMA to SFHA mapping on several FIRM panels upstream of the SFWMD structures as part of the SFL study do not appear consistent or warranted based on the methodologies applied and justification provided by FEMA elsewhere within Palm Beach County.

The information presented herein for Task 5 as well as Tasks 2, 3, and 4 will be compiled in Task 6 to document the key findings, conclusions, and recommendations regarding future coordination with FEMA.

6. References

National Oceanic & Atmospheric Administration (NOAA), 2020. <https://coast.noaa.gov/hurricanes/#map=4/32/-80>.

FEMA Document	Date	Description	Reference #
SFL Coastal Study Documents			
Coastal Discovery Report	Apr 2015	Presents available data and information considered by FEMA for inclusion in the updated coastal study.	[1]
Intermediate Data Submittal (IDS) Reports			
#1 Section 1 - Technical Approach	Nov 2014	Introduces the major technical study components contained in IDS Report #1, Sections 2-7.	[2]
Section 2 - Digital Elevation Model (DEM)	Mar 2016	Discuss topographic and bathymetric data sets, DEM development, and creation of the finite element model mesh utilized in the SWAN+ADCIRC modeling, WHAFIS modeling, and coastal hazard analyses.	[3]
Section 3 - Validation Storm Selection	Feb 2015	Presents wave and water level data sets and the methodology applied to develop the studys validation storm suite for the SWAN+ADCIRC modeling.	[4]
Section 4 - Study Area & Site Reconnaissance	May 2015	Details site reconnaissance performed and the procedure followed to identify coastal structures and to delienate the primary frontal dune (PFD).	[5]
Section 5 - JPM-OS Probablistic Model Development	Jun 2015	Documents the storm climatology and initial probabilistic model development.	[6]
Section 6 - Tropical Analysis & Forcing Development	Feb 2015	Presents the methodology applied to develop wind and pressure fields as inputs to the SWAN-ADCIRC modeling.	[7]
Section 7 - Hydrodynamic & Wave Model Development	Jan 2016	Details the wave and hydrodynamic storm surge model and mesh development methods.	[8]
#2 Section 1 - Wave & Hydrodynamic Model Validation	Feb 2017	Describes the methodology and results of the wave and hydrodynamic modeling validation.	[9]
Section 2 - JPM-OS	Oct 2016	Describes development of the representative stor set and associated annual recurrence rates (return period) of storms.	[10]
#3 Section 1 - Production Runs	Jun 2018	Describes the SWAN+ADCIRC modeling of the synethetic storms developed as part of the JPM-OS analysis. The modeling resulted in total maximum water levels and wave conditions for return period storms.	[11]
Section 2 - Low-Frequency Analysis	Jul 2018	Documents the methodology used to define still water elevations (SWEL) throughout the SWAN+ADCIRC modeling domain for low-frequency (2-, 1-, and 0.2-percent-annual-chance) storm events.	[12]
Section 3 - Regional Fequency Analysis of Tide Gage Water Levels	Jul 2019	Documents the methodology used to define still water elevations (SWEL) throughout the SWAN+ADCIRC modeling domain for high-frequency (50-, 20-, 10-, and 4-percent-annual-chance) storm events.	[13]
#4,5 Coastal Hazard Analysis	Oct 2019	Decribes the analyses of overland wave propagation, wave runup, wave overtopping, coastal structures, storm induced erosion used to define special flood hazard araes (SFHA) and delineate flood zones boundaries.	[14]
Preliminary Flood Insurance Study (FIS)	Dec 2019	Summarizes the general framework of the study, engineering methods considered in the study, and mapping methods.	[15]
Preliminary Flood Insurance Rate Map (FIRM) Panels	Dec 2019	Maps depicting SFHA, flood zones, and base flood elevations (BFE) resulting from the study. Maps provide a level of detail that individual building and parcels can be identified.	[16]
FEMA Guidance Documents			
Atlantic Ocean & Gulf of Mexico Coastal Guidelines Update	Feb 2007	Technical guidance governing the breadth of the modeling and analysis for coastal study updates.	[17]
Guidance for Coastal Flood Hazard Analysis & Mapping (CFHAM)			
Sheltered Waters	Feb 2008	Guidance for analyzing flood harzards (primarily 1-percent-annual chance- storm events) within sheltered water areas.	[18]
Overland Wave Propagation	Nov 2015	Guidance on applying the WHAFIS model, defining input parameters, and interpreting model results.	[19]
Erosion	Feb 2018	Guidance on methods available to estimate profile changes for erodible shorelines due to storm events.	[20]
Coastal Floodplain Mapping	Nov 2019	Guidance on delineating coastal flood zones and defining BFE's.	[21]
Coastal Water Levels	May 2016	Guidance on extracting stillwater level (SWL) data from measured water levels and on determining SWL where storm surge processes dominate.	[22]
Coastal Structures	Nov 2019	Guidance on methods available to analyze the stability and effects of coastal structures during the 1-percent-annual-chance storm event.	[23]
Coastal General Study Considerations	Nov 2019	Guidance provides an overview of coastal flooding processes and describes general considerations for FEMA coastal flood hazard studies.	[24]
Determination of Wave Characteristics	Feb 2019	Guidance on determining wave characteristics that are required for a coastal hazard analysis.	[25]
Wave Height Analysis for Flood Insurance Studies (WHAFIS)			
WHAFIS Technical Documentation Version 3.0	Sep 1988	User manual for the WHAFIS model.	[26]
Supplementary WHAFIS Documentation Version 4.0	Aug 2007	Supplemental information for a later version of the WHAFIS model.	[27]