Modeling to Support an Appeal of FEMA Preliminary Flood Insurance Rate Maps

Validation Storm Improvements (Deliverable 4.2)
Task Order #1778-05

August 20, 2021 | 13134.202.R1.RevA

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13134.202.R1.RevA

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Revision	Date	Status	Comments	Prepared	Reviewed	Approved
A	2021-04-16	Draft		TH	GT	TH

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1. Task Overview

During a Review and Evaluation of the Federal Emergency Management Agency's (FEMA) Coastal Flood Risk Study (Task Order No. 1778-01), Baird identified several issues related to the accuracy of the modeling that was conducted by FEMA in support of the preparation of preliminary Florida Insurance Study (FIS) reports and Flood Insurance Rate Maps (FIRMs) for eastern Palm Beach County (County). These modeling issues may have resulted in erroneous 1-percent annual chance water surface elevations [i.e., Base Flood Elevations (BFE)] and/or FEMA assigning an incorrect flood hazard flood zone to properties.

For Task 4 of Task Order 1778-05, Modeling to Support and Appeal of FEMA Preliminary Flood Insurance Rate Maps, Baird's specific objective was to review FEMA's validation of the ADCIRC model.

2. Review of Validation

Model uncertainty, applied in post-processing results, is based in part on a study-specific Model Validation Error, calculated as the standard deviation of the differences between simulated and measured water surface elevations at observation points used in the model validation analysis for Hurricanes Andrew, Betsy, David, Georges, and Wilma (244 observation points throughout FEMA's SFL Study area). Three different issues related to how model uncertainty was computed were identified and are as follows:

1. The Model Validation Error is applied uniformly across the SFL Study area by FEMA, despite the model validation appearing to be spatially variable. That is, higher model validation (less error) is presented for Palm Beach County in the northern portion of the SFL Study area.

2. Two types of water level data are considered within the model validation: 1) hydrograph data from gage measurements, and 2) highwater marks (HWM) from post-storm survey measurements. The different sources are treated the same, even though it is acknowledged that HWMs are less reliable.

3. 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.

A single Model Validation Error was applied even though the model validation results are spatially variable. This is discussed more in the next section.

Figure 1 compares modeled and measured peak water elevations while providing additional detail regarding the storm and type or measurement. Solid symbols and "x" indicate peak water levels obtained from gage measurements; open symbols indicate data from HWM.

As **Figure 1** shows, there was greater difference between modeled and measured water levels along the coastlines of Biscayne Bay in Miami-Dade County and Everglades National Park in Monroe County as compared to elsewhere in the SFL Study area. The modeled water levels range 2 to 3+ feet above/below the measured data. These differences are primarily associated with Hurricane Andrew in Miami-Dade County and Hurricane Wilma in Monroe County.

The modeled water levels agree more closely with gage measurement data at lower water levels as compared to higher water levels. This is most evident for Hurricanes Andrew and Wilma as shown by the increased clustering of data point along the black, diagonal line at the lower left corner of **Figure 1** as compared to moving toward the upper, right corner. Lower water levels generally indicate less influence from storm surge.

The modeled water levels agree more closely with the gage measurement data as compared to the HWM data. This is shown by the increased clustering of data points along the black, diagonal line for hydrograph data (solid symbols) as compared to the increased scatter for the HWM data (open symbols) in **Figure 1**. This may be related to the inherent lower level of accuracy and/or lower reliability of HWM data collected manually during post-storm damage assessments as well as model uncertainty in simulating higher water levels (i.e. storm surge) where HWM are typically collected.

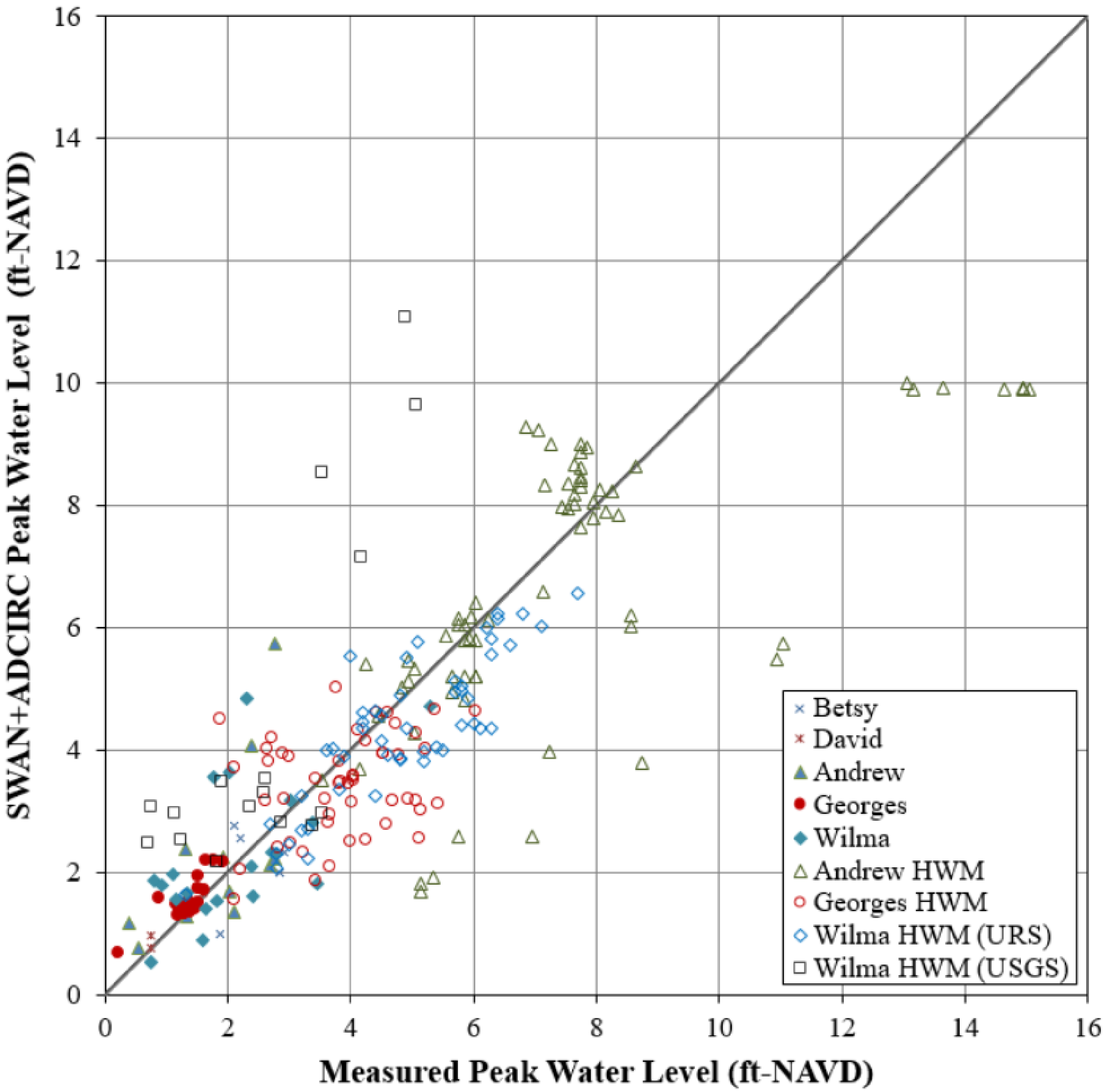

Figure 1. Measured-to-Modeled Peak Water Level Comparison for All Storms (FEMA, 2017)

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.

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**, 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.

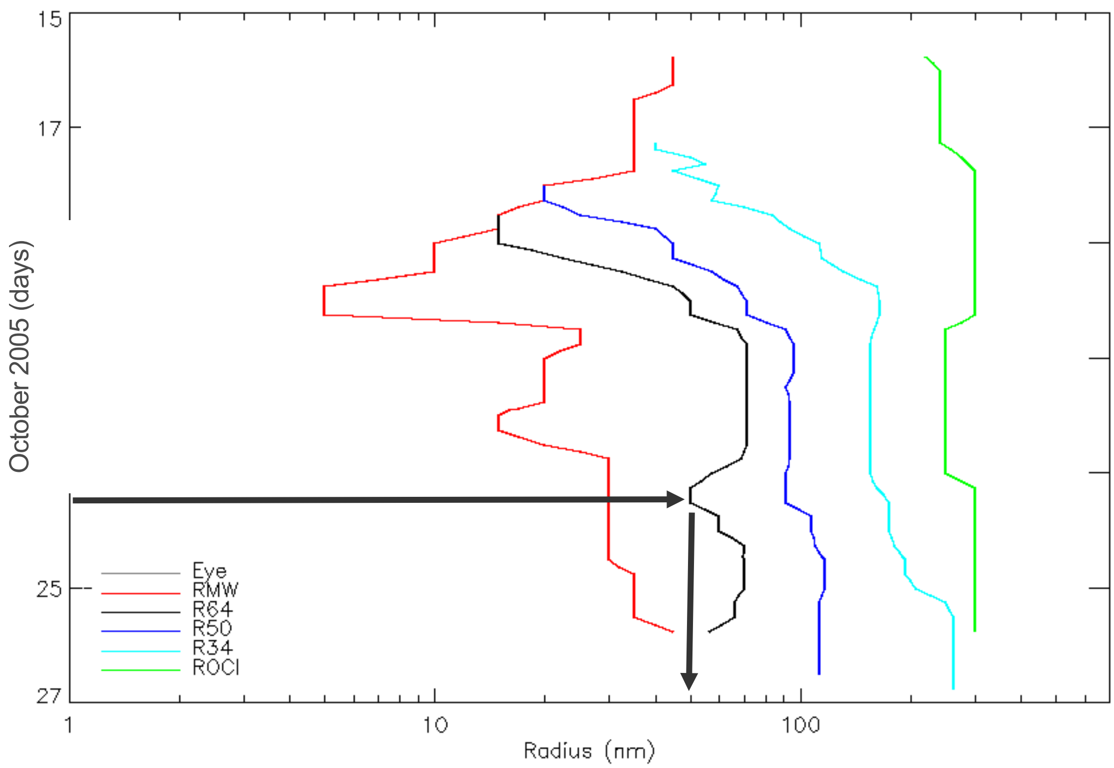

Figure 2. Hurricane Wilma - Wind Field Time Series (NOAA, 2020)

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 3** through **Figure 7**. This analysis is summarized in **Table 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 1. Measured Water Level Location 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%

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

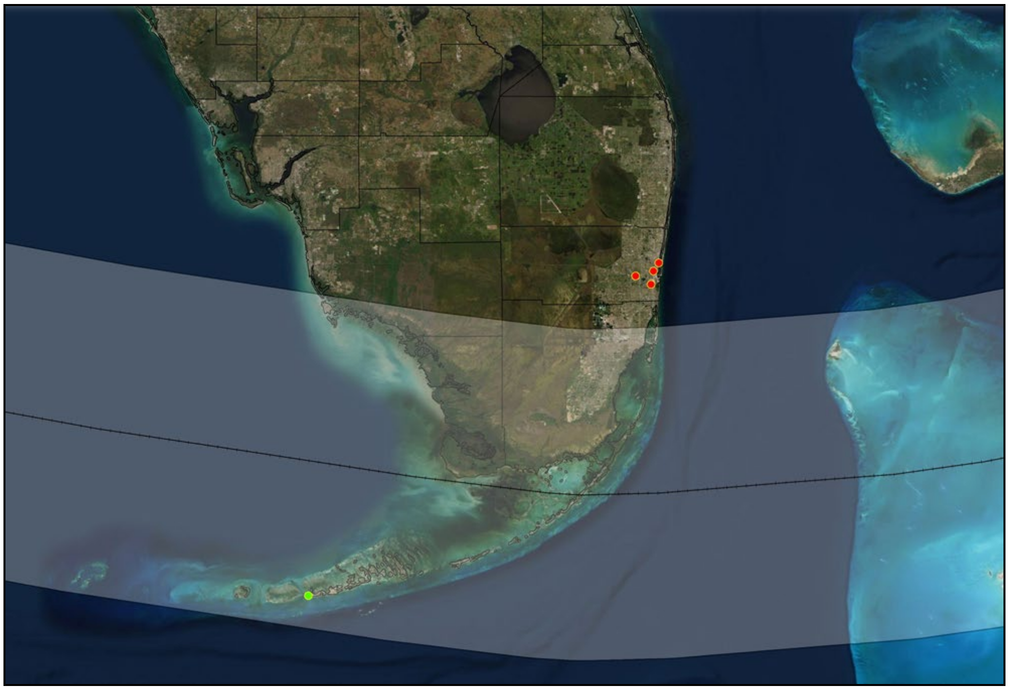

Figure 3. Measured Water Level Locations relative to Storm Track Offset – Hurricane Betsy

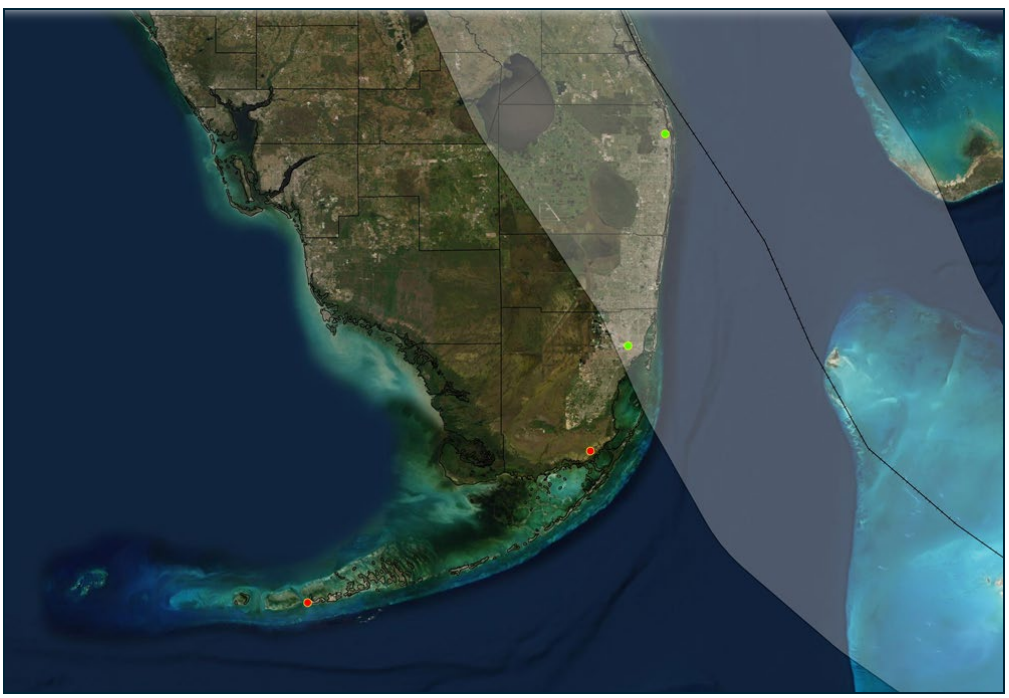

Figure 4. Measured Water Level Locations relative to Storm Track Offset – Hurricane David

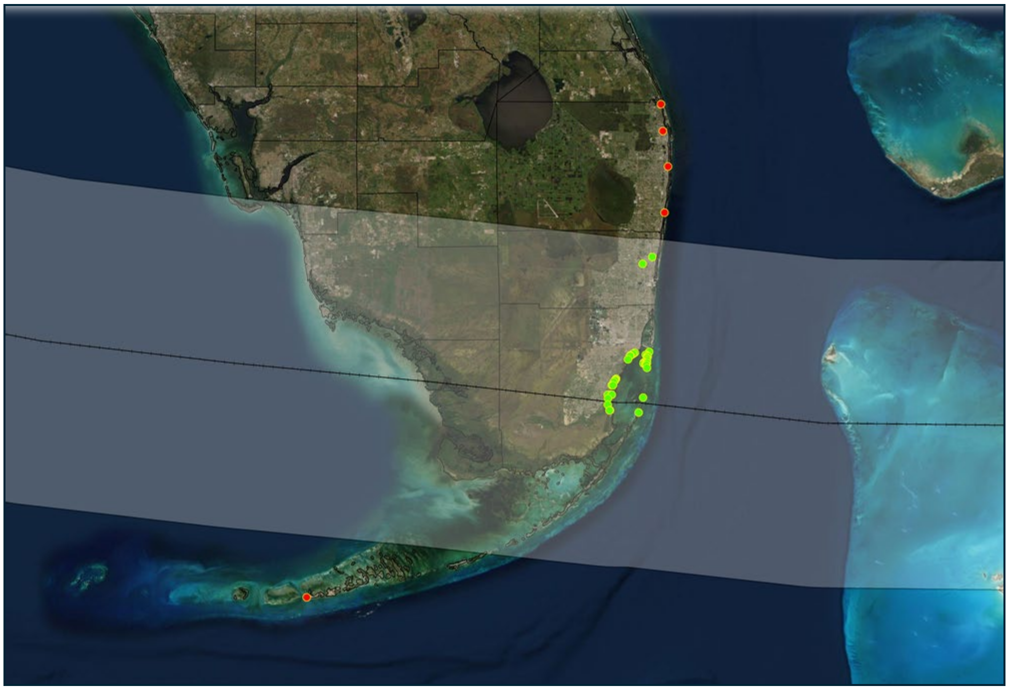

Figure 5. Measured Water Level Locations relative to Storm Track Offset – Hurricane Andrew

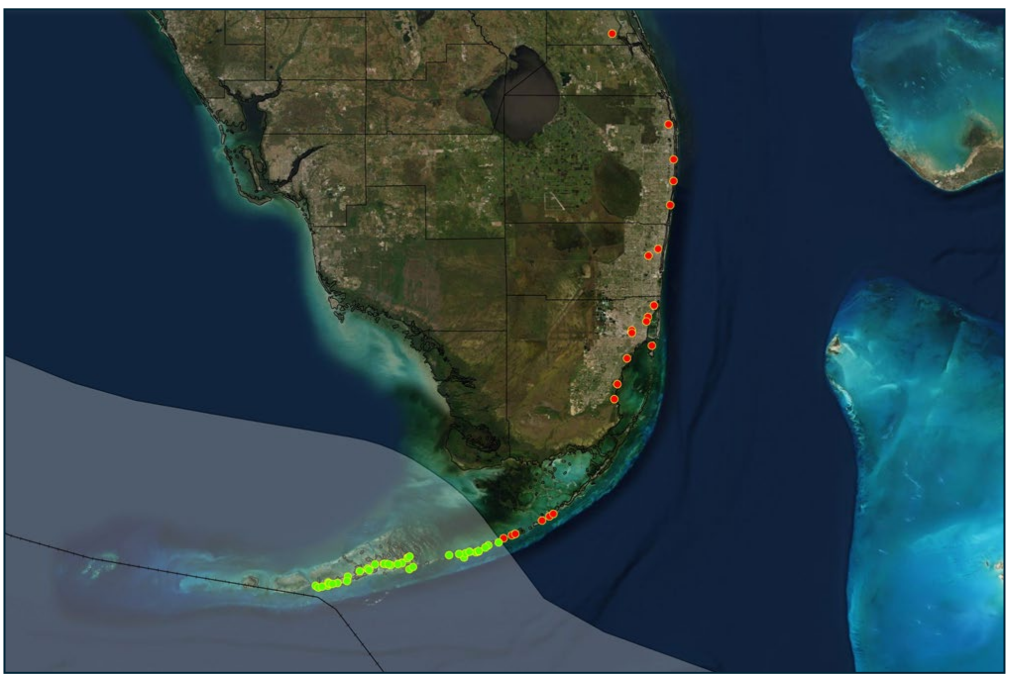

Figure 6. Measured Water Level Locations relative to Storm Track Offset – Hurricane Georges

Figure 7. Measured Water Level Locations relative to Storm Track Offset – Hurricane Wilma

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 because of approximations in physical processes. 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. 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 1**, 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. 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 that 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. 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

Review of the model uncertainty and bias for each of the counties and with respect to the validation storms provides insight on the spatial variability of the uncertainty (see **Table 3**).

The model uncertainty within Palm Beach County was the lowest of the four counties and 60% less than the uncertainty for the overall study area. The greatest uncertainties occurred within Miami-Dade and Monroe Counties, which were attributed to Hurricanes Andrew and Wilma, respectively.

Hurricanes Andrew and Wilma resulted in a model uncertainty of 2.00 feet and 1.41 feet, respectively, for the SFL Study. Hurricane Wilma was omitted from the model validation for the ECCFL study having had resulted in an uncertainty of approximately 1.0 foot.

The lowest uncertainties for storms were associated with Hurricanes Betsy and David, but the validations were limited to 4-5 gages that were available for each of these storms. For each of the storms, one of the gages was NOAA's Key West station. However, FEMA reported that the NOAA Key West gage is not suitable "to capture the maximum surge levels for storms that impact the Atlantic coastline".

Model bias was assessed by FEMA to determine whether the model validation tends to over or under predict water levels. Bias was represented by FEMA as the average of the differences between modeled and measured peak water levels. The average of the overall study area reported by FEMA was -0.25 feet, which FEMA explained as a slight model bias of under predicting water levels. Within Miami-Dade County, the average was -0.52 feet which can be largely attributed to the landfall of Hurricane Andrew in Miami. Within Palm Beach County, the average was +0.25 feet suggesting an over prediction of modeled water levels. No adjustments were made by FEMA to account for spatial variability of model bias within the study area or the influence of the apparent outlier (Miami-Dade County).

Table 3. FEMA Model Uncertainty and Bias

County	Uncertainty * (feet)	Bias (feet)	Validation Storm	Uncertainty* (feet)	Bias (feet)
Palm Beach	0.63	0.25	**Betsy (1965)**	0.72	-0.26
Broward	0.64	0.05	**David (1979)**	0.13	0.07
Miami-Dade	1.84	-0.52	**Andrew (1992)**	2.00	-0.65
Monroe	1.36	-0.15	**Georges (1998)**	0.99	-0.24
Overall	**1.54**	**-0.25**	**Wilma (2005)**	1.41	0.09
*uncertainty = model skill			**Overall**	**1.54**	**-0.25**

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 8**. Clustering of points along the diagonal line in **Figure 8** 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.

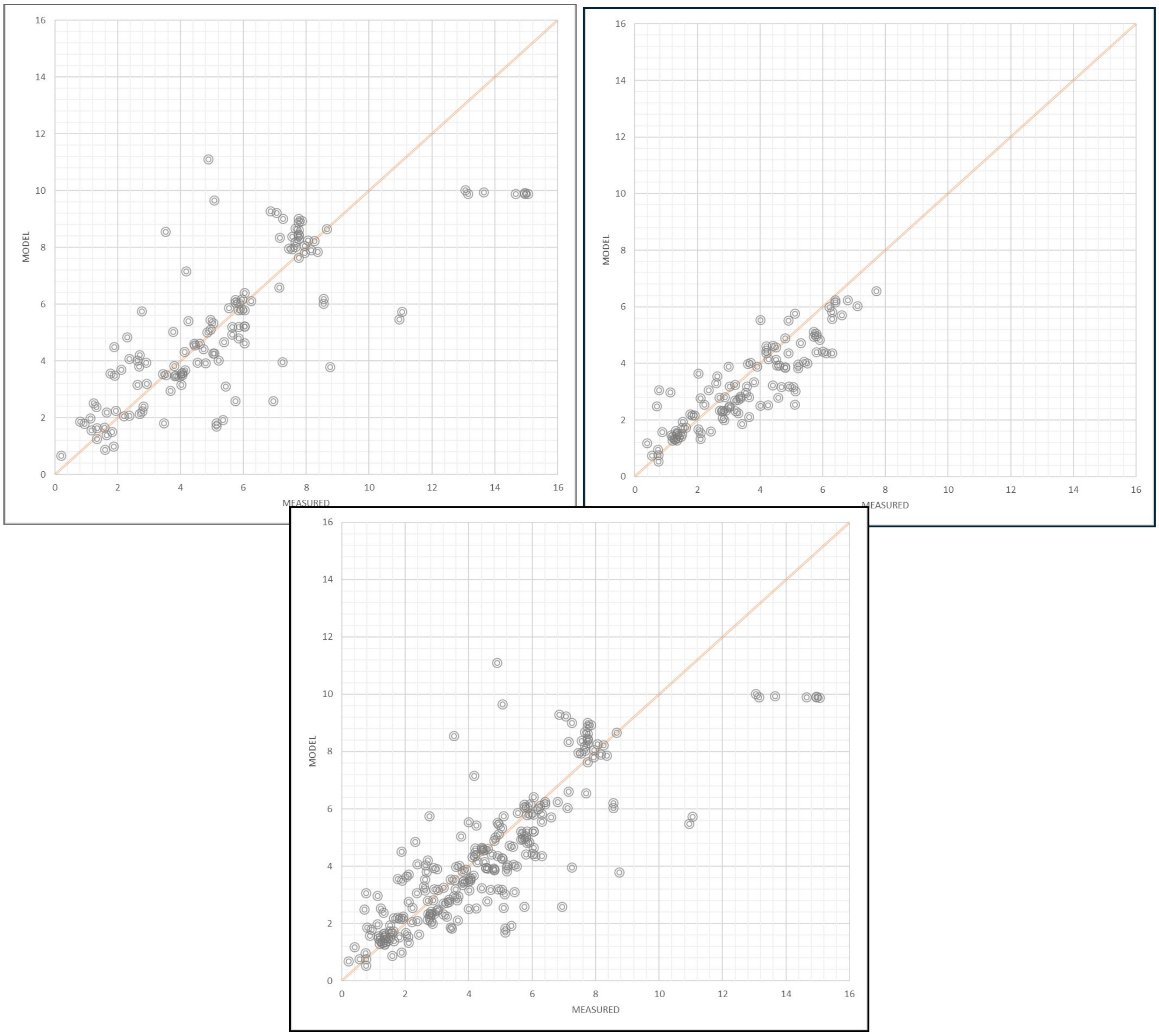

Figure 8. Measured-to-Modeled Peak Water Level (top right panel: Within Offset; top left panel: Outside Offset; bottom panel: FEMA/all)

3. Summary

The analysis presented herein demonstrates that FEMA's ADCIRC+SWAN model had limited accuracy in simulating storm surge. This limitation may have contributed to greater model uncertainty and ultimately increased statistical SWEL.