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July 9, 2021

Via Email: michael.taylor@aecom.com

Mapping Partner
c/o Michael Taylor
AECOM
1360 Peachtree Street Northeast, Suite 500
Atlanta, GA 30309

Dear Mr. Taylor,

Subject: Appeal of Preliminary Flood Insurance Rate Maps and Flood Insurance Study for Palm Beach County, Florida

Palm Beach County, Florida (County) respectfully submits the attached appeal of the Federal Emergency Management Agency's (FEMA) Preliminary Flood Insurance Rate Maps (FIRMs) and Flood Insurance Study that were published on December 20, 2019. This appeal is being submitted within the 90-day appeal period that started April 16, 2021. The attached documents provide detailed information demonstrating that FEMA's proposed flood hazard determinations are scientifically and technical incorrect due to fundamental errors made in the modeling used to prepare the FIRMs.

In preparation for FEMA's 90-day appeal period, the County conducted a comprehensive review and evaluation of the data and methods used by FEMA to prepare the preliminary FIRMs. On October 5, 2020, the County transmitted three documents from its review and evaluation to FEMA and its technical team. On November 17, 2020, AECOM, FEMA's Mapping Partner, held a meeting with FEMA and the County's technical team to enable a discussion of the County's key findings. Many of the County's concerns and questions were not able to be addressed during the meeting and required additional research. During the meeting, the County also expressed a strong desire to work collaboratively with FEMA to resolve the County's technical issues and concerns prior to the formal appeal period, however, FEMA declined this opportunity. To date, FEMA has not provided a written response to any of the information provided by the County.

Being a coastal community dedicated to responsible and modern floodplain management and a participant in the National Flood Insurance Program since 1979, Palm Beach County considers FEMA flood zone designations to be extremely important. While the County understands the need for FEMA to incorporate updated data and information into FIRMs, it is imperative that FEMA employs accurate data and appropriate methodologies when developing updated coastal flood zones. Storm surge and wave model configurations, assumptions and techniques can result in higher than desirable uncertainty, unreliable water levels and unreliable mapping of flood risks, all of which can have significant implications for County residents and businesses. Accuracy of the FIRMs is critically important to Palm Beach County and therefore the fundamental errors presented in the attached documents must be corrected by FEMA.

Palm Beach County is committed to work collaboratively with FEMA to ensure that flood risk in the County is accurate and appropriate. Palm Beach County urges FEMA to correct and reissue the 2019 Preliminary FIRMs for Palm Beach County. Please include Jeremy McBryan, County Water Resources Manager (561-355-4600; jmcbryan@pbcgov.org) in any communication regarding this appeal.

Sincerely,

Verdenia C. Baker

Verdenia C. Baker
County Administrator

Attachment

cc: Members, Palm Beach County Board of County Commissioners
Patrick Rutter, Assistant County Administrator, Palm Beach County
Todd Bonlarron, Assistant County Administrator, Palm Beach County
Doug Wise, Building Division Director/Floodplain Administrator, Palm Beach County
Jeremy McBryan, County Water Resources Manager
Mark Vieira, Federal Emergency Management Agency
Conn Cole, State Floodplain Manager, Florida Division of Emergency Management

Appeal of Preliminary Flood Insurance Rate Maps and Flood Insurance Study for Palm Beach County, Florida

July 2021

Submitted to:
Mapping Partner
c/o Michael Taylor, AECOM
1360 Peachtree Street Northeast, Suite 500
Atlanta, GA 30309
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Submitted by:
Palm Beach County, Florida

Contact:
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1.0 Introduction

On December 20, 2019, the Federal Emergency Management Agency (FEMA) published Preliminary Flood Insurance Rate Maps (FIRMs) and a Flood Insurance Study (FIS) report for Palm Beach County, Florida (County). The new or modified flood hazard information provided in the Preliminary FIRMs and FIS report is based on FEMA's Coastal Flood Risk Study Project for the South Florida Study Area (SFL Study) which included Palm Beach, Broward, Miami-Dade and Monroe Counties.

The flood hazard determinations in the FIRMs and FIS report are subject to a 90-day statutory appeal period during which the community and/or individual property owners can submit an appeal presenting scientific or technical data demonstrating that FEMA's proposed flood hazard determinations are incorrect. The 90-day appeal period for Palm Beach County began on April 16, 2021.

In preparation for FEMA's 90-day appeal period, the County conducted a comprehensive review and evaluation of the data and methods used by FEMA to prepare the Preliminary FIRMs. On October 5, 2020, the County transmitted three documents from its review and evaluation to FEMA and its technical team. On November 17, 2020, AECOM held a meeting with FEMA and the County's technical team to enable a discussion of the County's key findings. Many of the County's concerns and questions were not able to be addressed during the meeting and required additional research. During the meeting, the County expressed a strong desire to work collaboratively with FEMA to resolve the County's technical issues and concerns prior to the formal appeal period, however, FEMA declined this opportunity. To date, FEMA has not provided a written response to the information provided by the County in October 2020.

In accordance with Title 44 of the Code of Federal Regulations (CFR) Sections 67.5 and 67.6 and 42 United States Code (USC) Section 4101, Palm Beach County's Preliminary FIRMs are eligible for appeal because the County is in possession of knowledge and information that indicates FEMA's proposed flood hazard determinations are scientifically and technical incorrect due to fundamental errors made in the modeling used to prepare the FIRMs.

Being a coastal community dedicated to responsible and modern floodplain management and a participant in FEMA's National Flood Insurance Program since 1979, the County considers FEMA flood zone designations to be extremely important. While the County understands the need for FEMA to incorporate updated data and information into FIRMs, it is imperative that FEMA employs accurate data and appropriate methodologies when developing updated coastal flood zones. Storm surge and wave model configurations, assumptions and techniques can result in higher than desirable uncertainty, unreliable water levels and unreliable mapping of flood risks, all of which can have significant implications for County residents and businesses. Accuracy of the FIRMs is critically important to Palm Beach County and therefore the fundamental errors presented in the attached documents must be corrected by FEMA.

Palm Beach County is committed to work collaboratively with FEMA to ensure that flood risk in the County is accurate and appropriate. This document and its attachments show "that alternative methods or applications result in more correct estimates of base flood elevations, thus demonstrating that FEMA's estimates are incorrect." (44 CFR §67.6 (a)). Palm Beach County urges FEMA to correct and reissue the 2019 Preliminary FIRMs for Palm Beach County.

2.0 Scope of Appeal

The scope of Palm Beach County's appeal includes all 52 Preliminary FIRM panels published by FEMA on December 20, 2021 as shown in **Figure 1** and listed in **Table 1**.

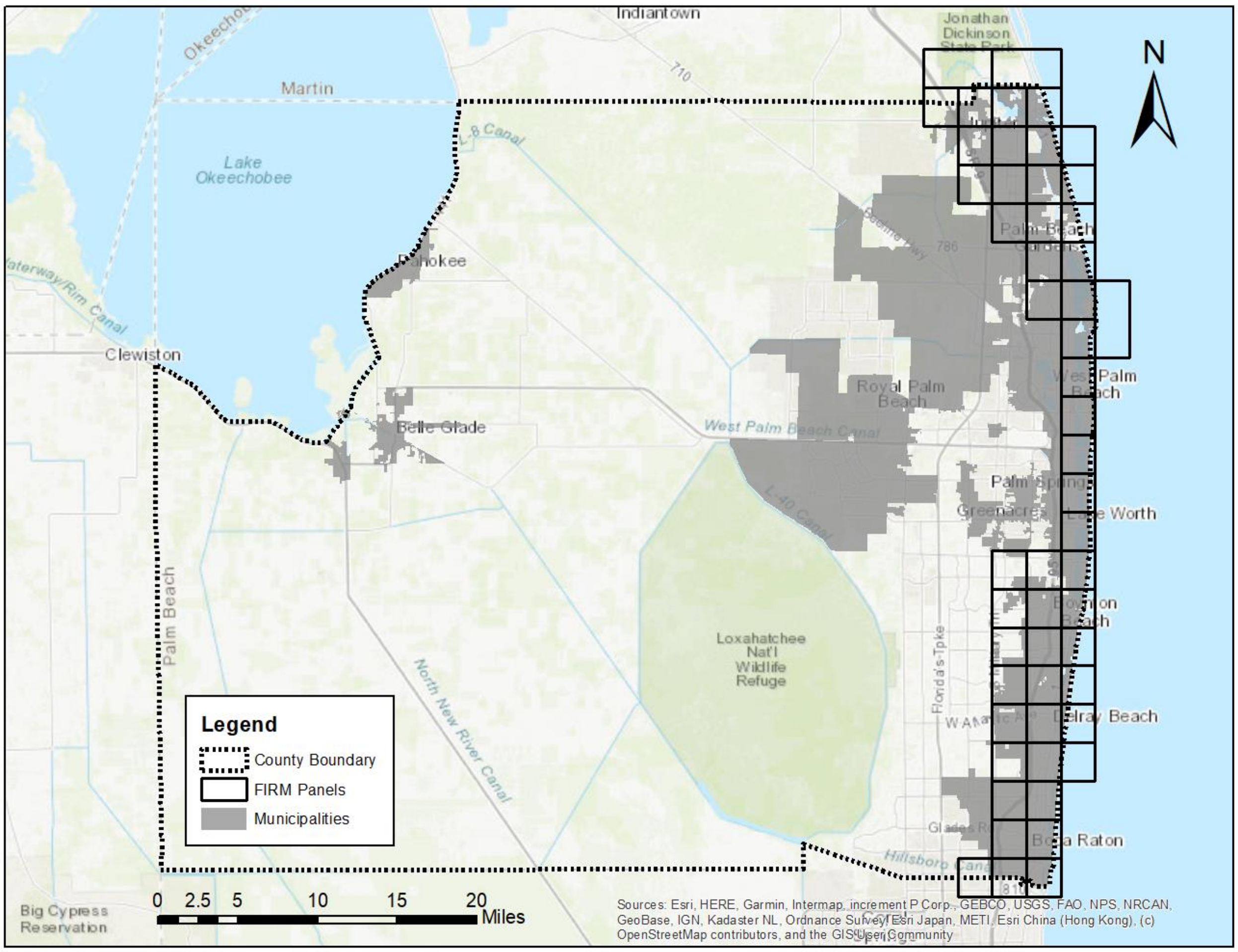

Figure 1. FIRM Panels included in Palm Beach County Appeal of FEMA's Preliminary FIRMs

Table 1. FIRM Panels included in Palm Beach County's Appeal of FEMA's Preliminary FIRMs

12099C0158G	12099C0191G	12099C0581G	12099C0789G	12099C0988G
12099C0159G	12099C0193G	12099C0583G	12099C0791G	12099C0989G
12099C0160G	12099C0376G	12099C0591G	12099C0793G	12099C0991G
12099C0167G	12099C0377G	12099C0593G	12099C0976G	12099C1159G
12099C0169G	12099C0379G	12099C0778G	12099C0977G	12099C1176G
12099C0178G	12099C0381G	12099C0779G	12099C0978G	12099C1177G
12099C0179G	12099C0383G	12099C0781G	12099C0979G	12099C1178G
12099C0180G	12099C0387G	12099C0783G	12099C0981G	12099C1179G
12099C0186G	12099C0391G	12099C0786G	12099C0983G	
12099C0187G	12099C0393G	12099C0787G	12099C0986G	
12099C0189G	12099C0395G	12099C0788G	12099C0987G	

3.0 Basis for Appeal

Palm Beach County's appeal of the 2019 Preliminary FIRMs is being submitted on the basis that FEMA's base flood elevations (BFEs) and Special Flood Hazard Area (SFHA) designations are scientifically and technically incorrect.

The primary error identified is that the wind and atmospheric pressure grid used in the modeling was far too coarse over a majority of Palm Beach County resulting in inaccurate model results. Other issues with the modeling were also identified and are included. In addition, there is now new topographic data that was not used in the modeling or mapping of the flood hazard areas. This document builds upon several reports prepared by Baird and Associates. The original reports are included as Appendices B, C and D.

4.0 Areas of Scientific and/or Technical Deficiency

This section provides a summary of the scientific and/or technical deficiencies, issues, and concerns with the data and methods used by FEMA to prepare the 2019 Preliminary FIRMs identified by Palm Beach County.

For each area of scientific and/or technical deficiency, the following are provided: 1) a description of the deficiency, 2) a description of why the data, methods and/or assumptions used by FEMA are scientifically and/or technically incorrect, 3) an explanation of alternative analysis using more correct data and methodologies, and 4) technical support indicating why alternative methods and data should be accepted as more correct.

4.1 Wind and Pressure Field Grid Resolution Inappropriate for Palm Beach County

Description of the Deficiency

According to FEMA, "The production run phase of the South Florida Storm Surge Study (SFLSSS) applies the SWAN+ADCIRC (ADCIRC version 52.30 with SWAN version 41.01) (Booij, et al., 1999; Luettich and Westerink, 2005; Dietrich, et al., 2011) coupled approach to simulate the time-dependent surge in response to time-varying wind, barometric pressure, and wave forces." (FEMA 2018). The wind and barometric pressure variables are applied to the model and based on one of two gridded data sets which were provided to FEMA from Ocean Weather, Inc. (OWI). According to reporting provided by FEMA, "Ocean Weather, Inc. (OWI) provided multiple sets of time-dependent atmospheric pressure and wind files for each synthetic storm simulation. A file with the extension ".pre" contained atmospheric pressure fields, and a file with extension ".win" contained wind velocity fields. One set of files with relatively coarse resolution, referred to as a basin scale, covered the entire model mesh, including the western North Atlantic Ocean, Caribbean Sea, and Gulf of Mexico. A second set of files covered a smaller area, referred to as regional scale, and provided more detailed pressure and wind inputs along the general vicinity of the storm track" (FEMA 2018). However, the detailed pressure and wind inputs did not cover the majority of Palm Beach County.

These files are provided in grided format and can be visualized as shown in **Figure 2** which shows the location of coarse and fine grids covering the County. The wind and atmospheric pressure field files used by FEMA do not cover Palm Beach County north of Boynton Inlet. Therefore, the storm surge and the wave model were forced using the coarser basin scale grid as compared to the rest of the SFL study area.

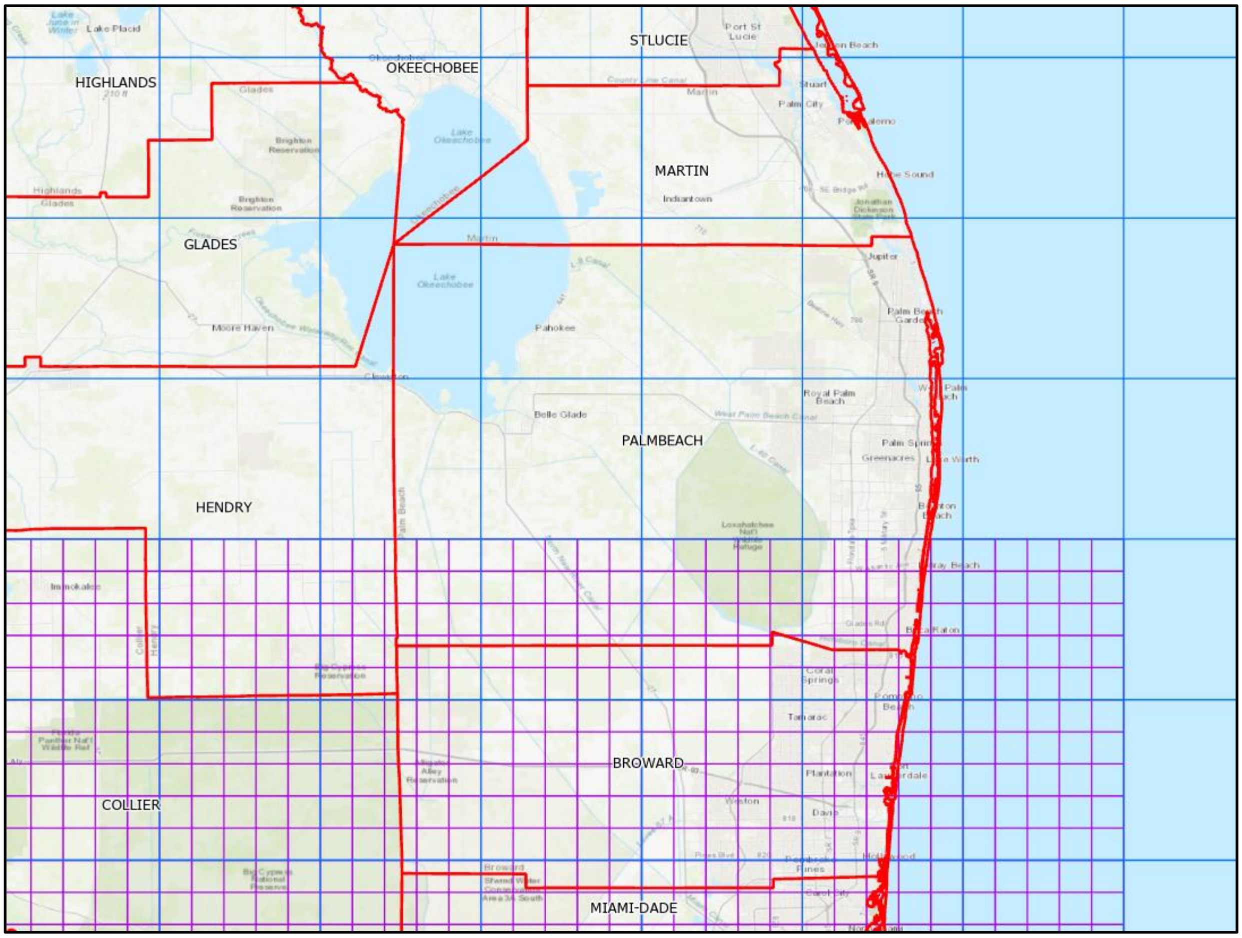

Figure 2. Wind and Pressure Field Grid Coverage for Palm Beach and Nearby Counties

Why FEMA's Data, Methods and/or Assumptions are Incorrect

FEMA's coarse (basin) grid was 5 times coarser than its finer (regional) grid that were used to define storm wind and pressure fields for the model. FEMA's basin grid for simulating storm wind and pressure fields covers the entire model domain (**Figure 3**) at a resolution of 0.25 degrees (approximately 15 nautical miles (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 4**). The northern boundary of FEMA's regional grid was located approximately 12 miles north of the Palm Beach / Broward county line; 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, in Palm Beach County, the storm surge and the wave model were forced using the coarser basin scale grid 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.

The highest 1% still water elevations (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 water surface elevations (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 line in **Figure 3** and **Figure 4**. The track was located north outside of the regional grid. The modeled wind field at landfall for Storm 21, extracted from FEMA's modeling data, is shown in **Figure 5** 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.

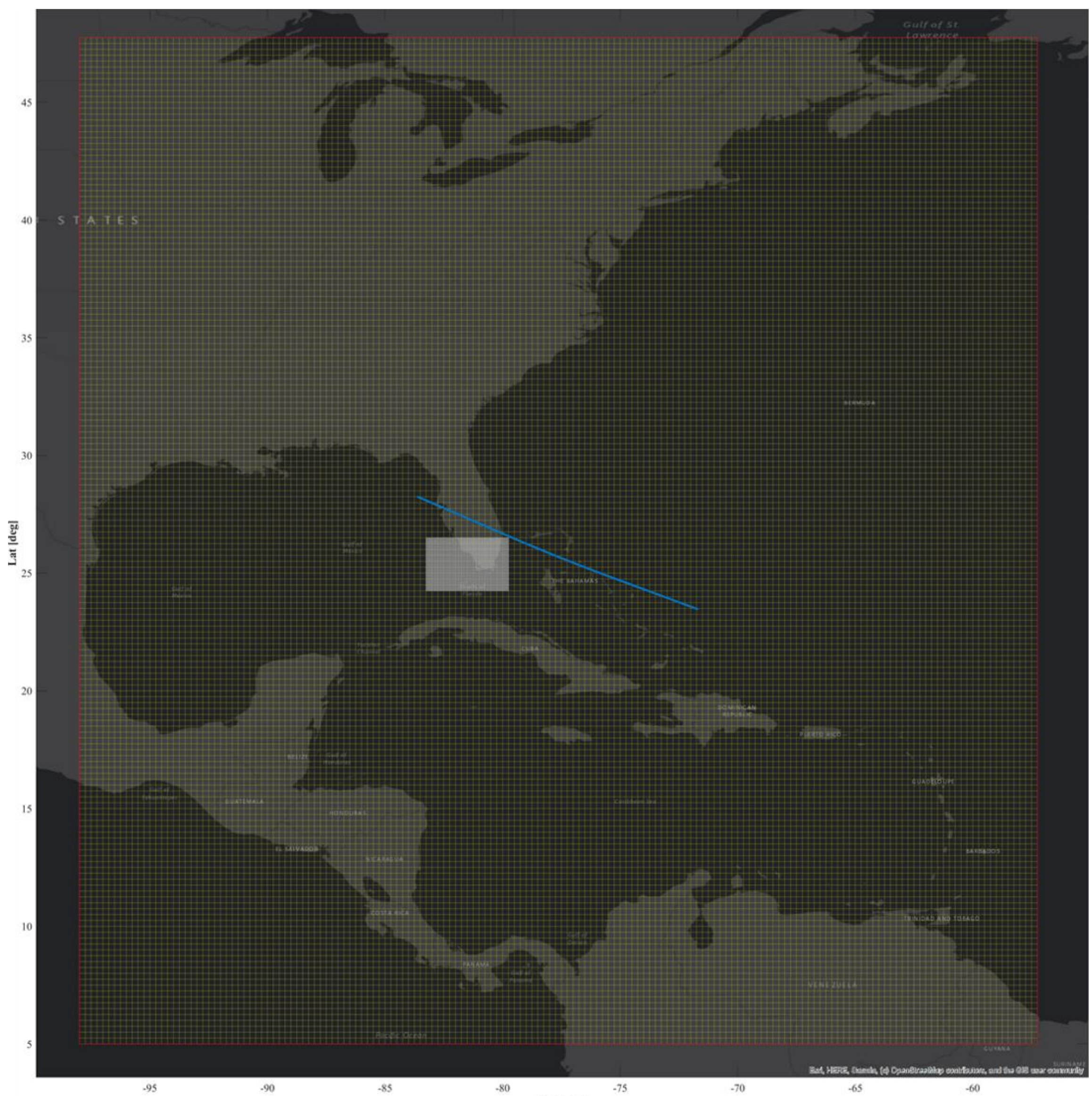

Figure 3. Wind and Pressure Field Grids Model Domain (Basin Grid is yellow and regional grid is white)

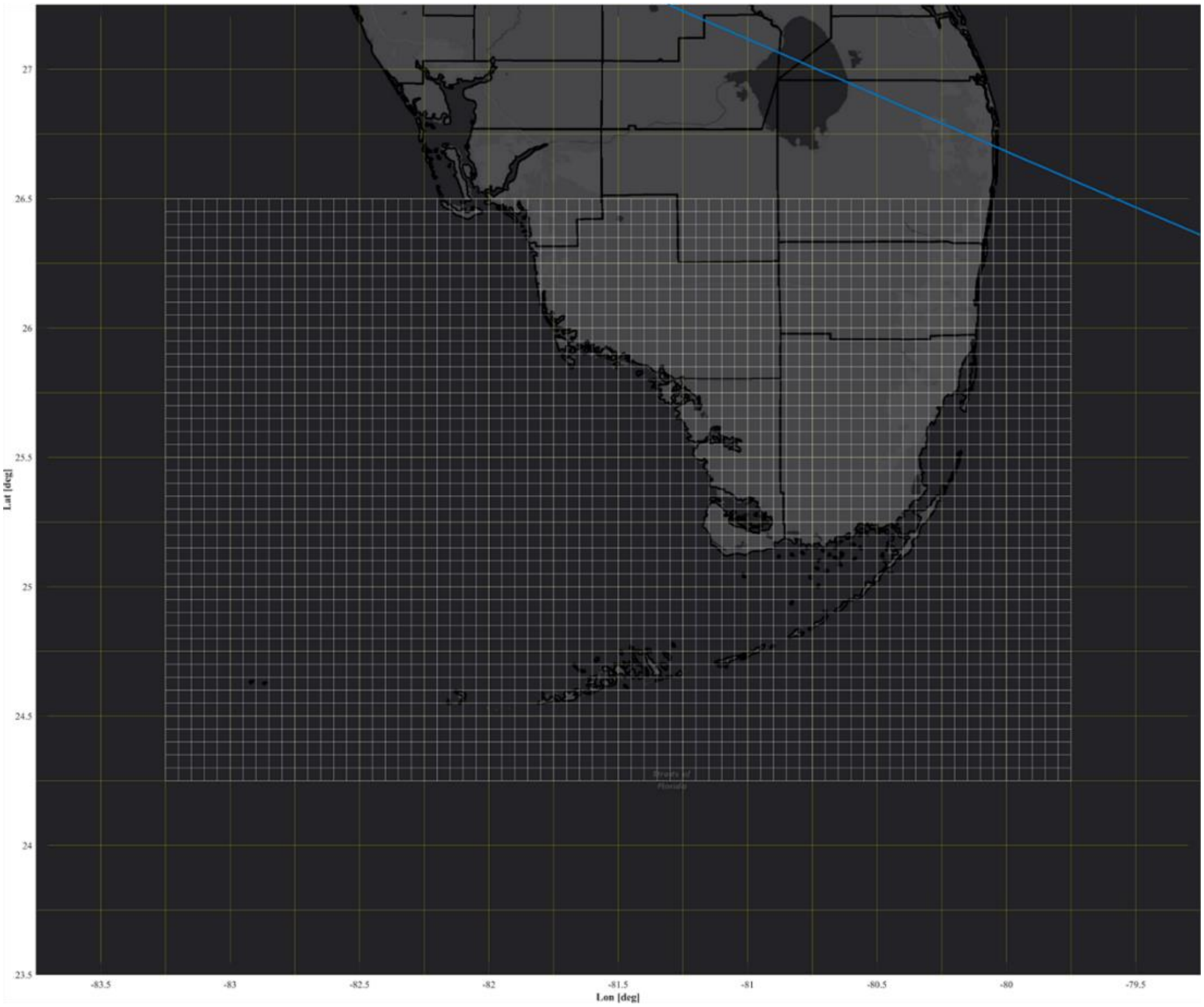

Figure 4. Wind and Pressure Field Regional Grids (basin grid is yellow and regional grid is white)

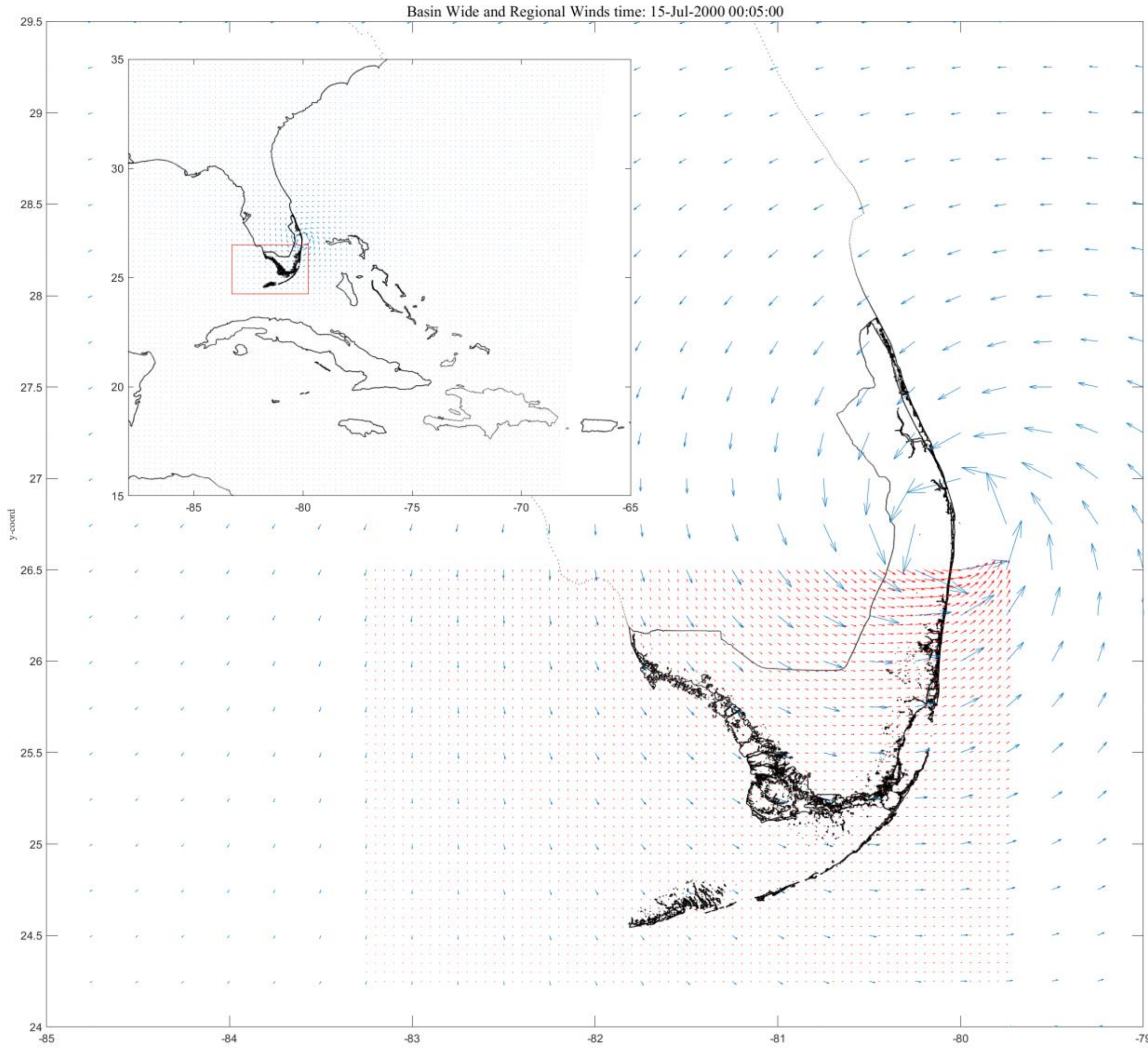

Figure 5. Wind Field Grids for Synthetic Storm 21 (basin grid vectors are blue and regional grid vectors are red)

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 6** shows landfall locations for each of 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.

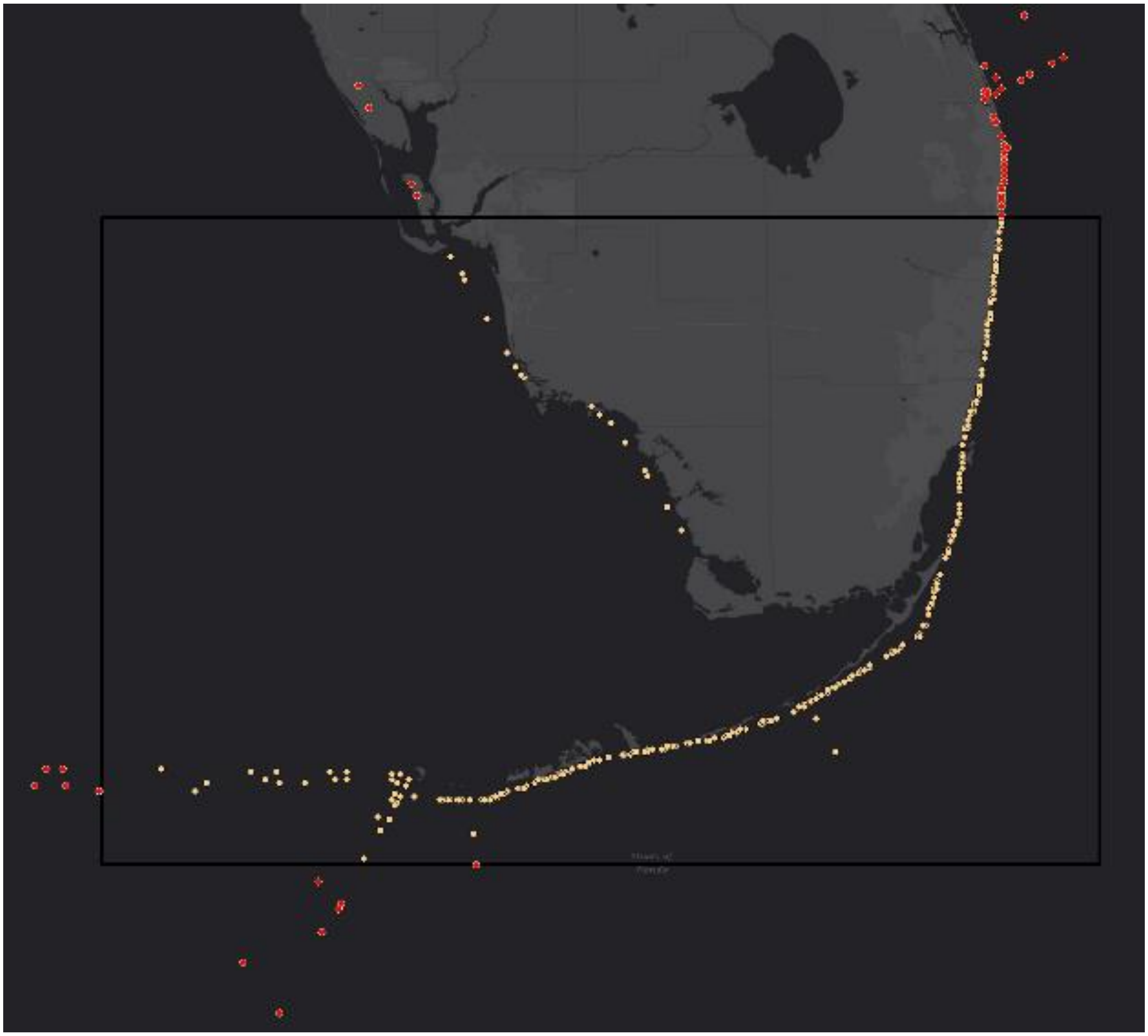

Figure 6. Wind and Pressure Field Regional Grid and Synthetic Storm Landfall Locations

Alternative Analysis Using More Correct Data and Methodologies

Since wind and pressure data was not produced at the finer resolution for the northern part of Palm Beach County, it was not possible to rerun the model with a finer grid. To show the impacts of the fine grid not covering the entire county, three storms were selected based on their return periods calculated in the Intracoastal Waterway (ICWW) near Boynton Inlet. **Figure 7** shows the tracks of the selected storms and the location where the return periods were calculated and **Figure 8** shows the return periods and WSE distribution using the results of all production runs from FEMA (Selected Storm 18, Storm 20 and Storm 21 marked as red) at this location.

All selected storms made landfall in northern Palm Beach County as shown in **Figure 7**. These events were chosen to bracket the potential impacts with particular focus to storms at the "tail" end (i.e., Storm 20, Storm 21) of the WSE/Return period distribution curve. By its nature, the distribution curve is very sensitive to the data points associated with higher return period events where the samples are scarce compared to lower return period events. For instance, the distribution curve presented in **Figure 8** has 352 data points with return periods below ~25 years (Storm 18). Only 40 points form the rest of the distribution curve.

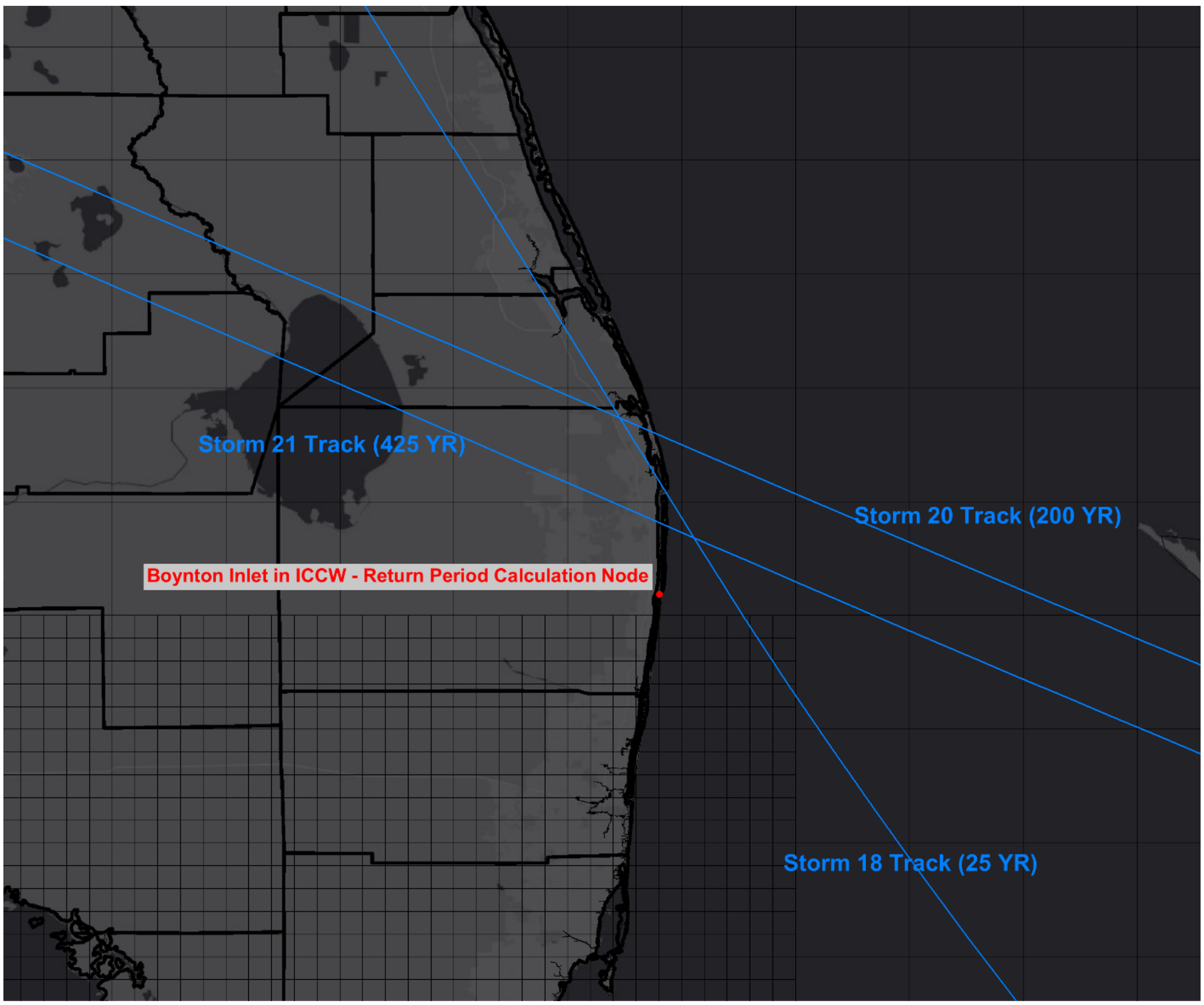

Figure 7. Storms tracks of events that were reanalyzed using only coarse wind and pressure grid.

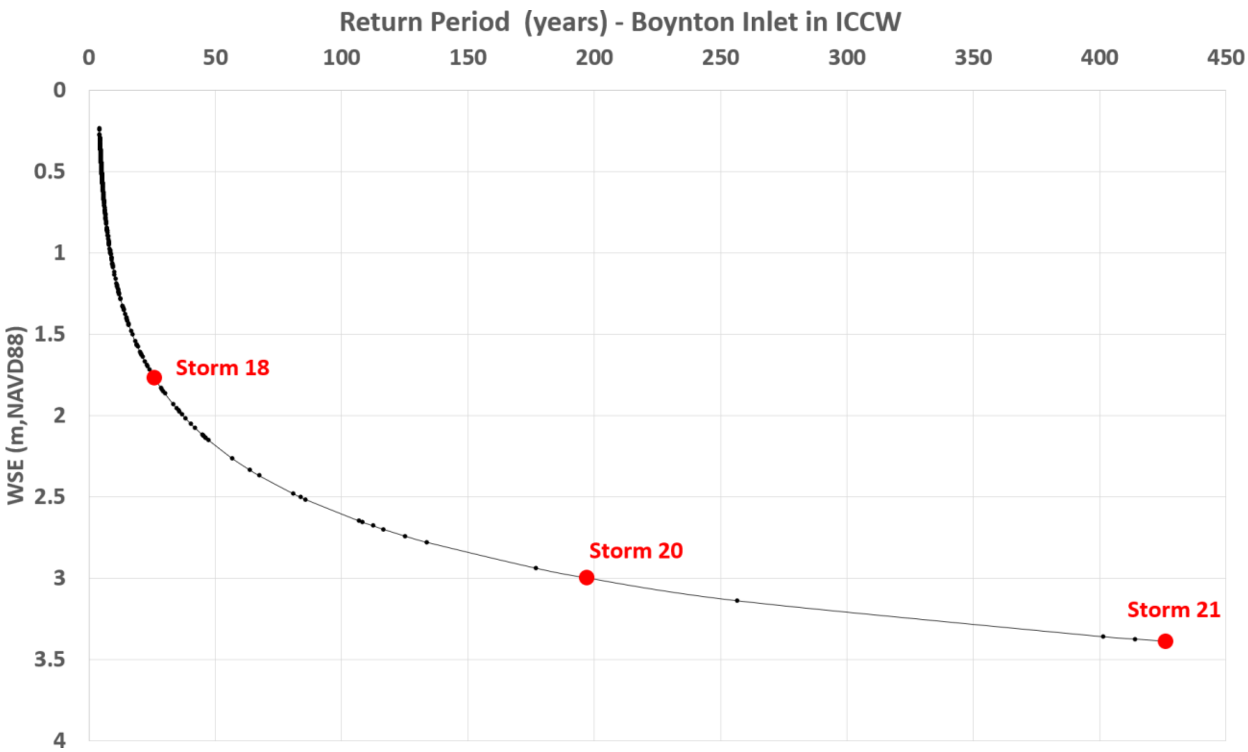

Figure 8. Return periods of reanalyzed storms.

The selected storms were run using the original setup files provided by FEMA. Additionally, reruns were completed using the same source codes for ADCIRC/SWAN (v52.30) as reported by FEMA.

Once re-simulations were complete, regional (fine) scale wind and atmospheric pressure inputs were removed leaving only the basin (coarse) scale wind and atmospheric pressure forcing as inputs to the model. No other changes were applied to FEMA's original setup files.

The impacts on the maximum WSE in Palm Beach County recorded during these simulations are presented in **Figure 9**, **Figure 11**, and **Figure 13** for Storm 18, Storm 20 and Storm 21 respectively. **Figure 10**, **Figure 12**, and **Figure 14** show the results over the entire fine grid area.

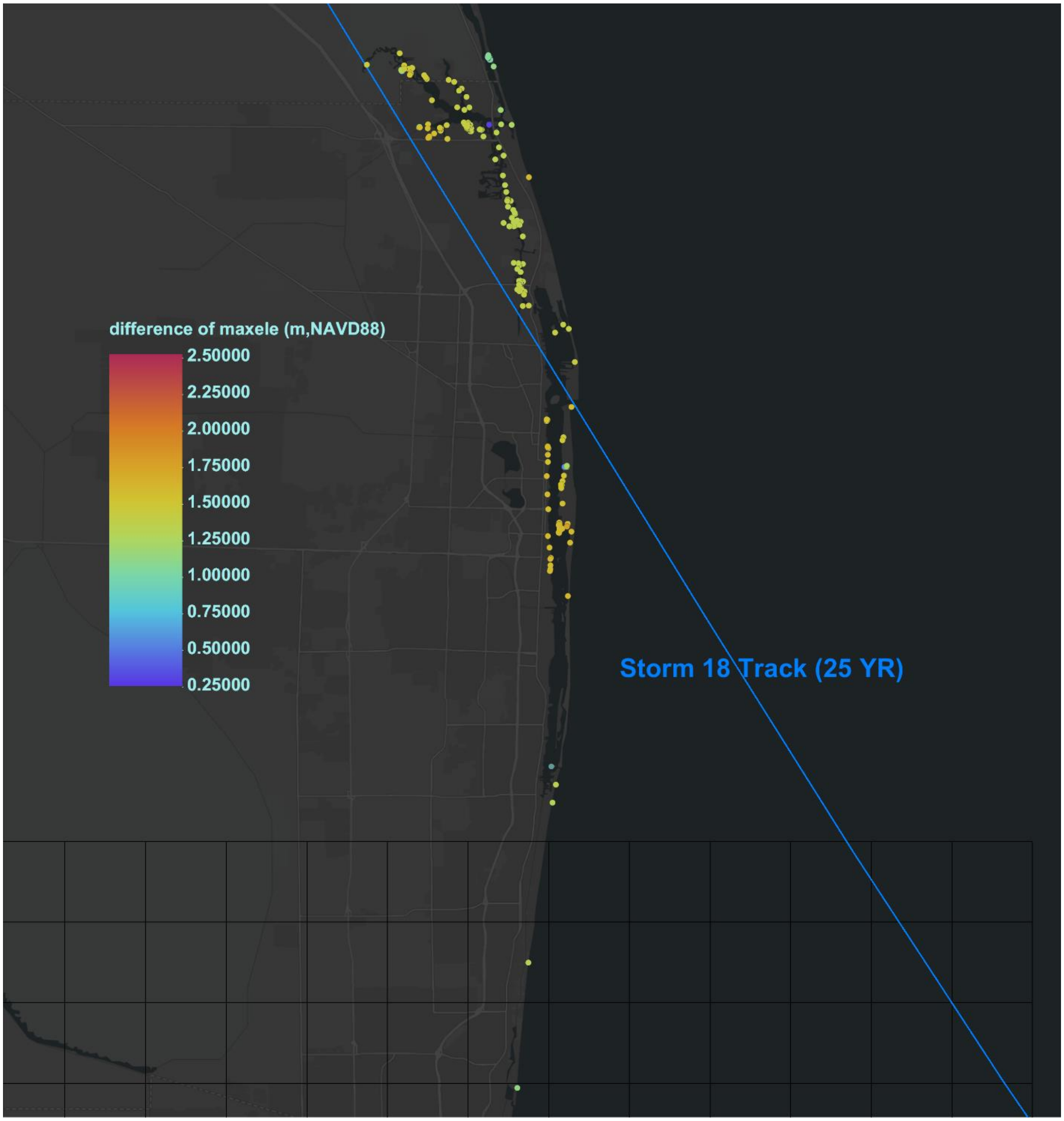

Figure 9. Maximum Water Surface Elevation Difference (meters) between fine and coarse wind and pressure grid for Storm 18 – Fine grid footprint shown for reference

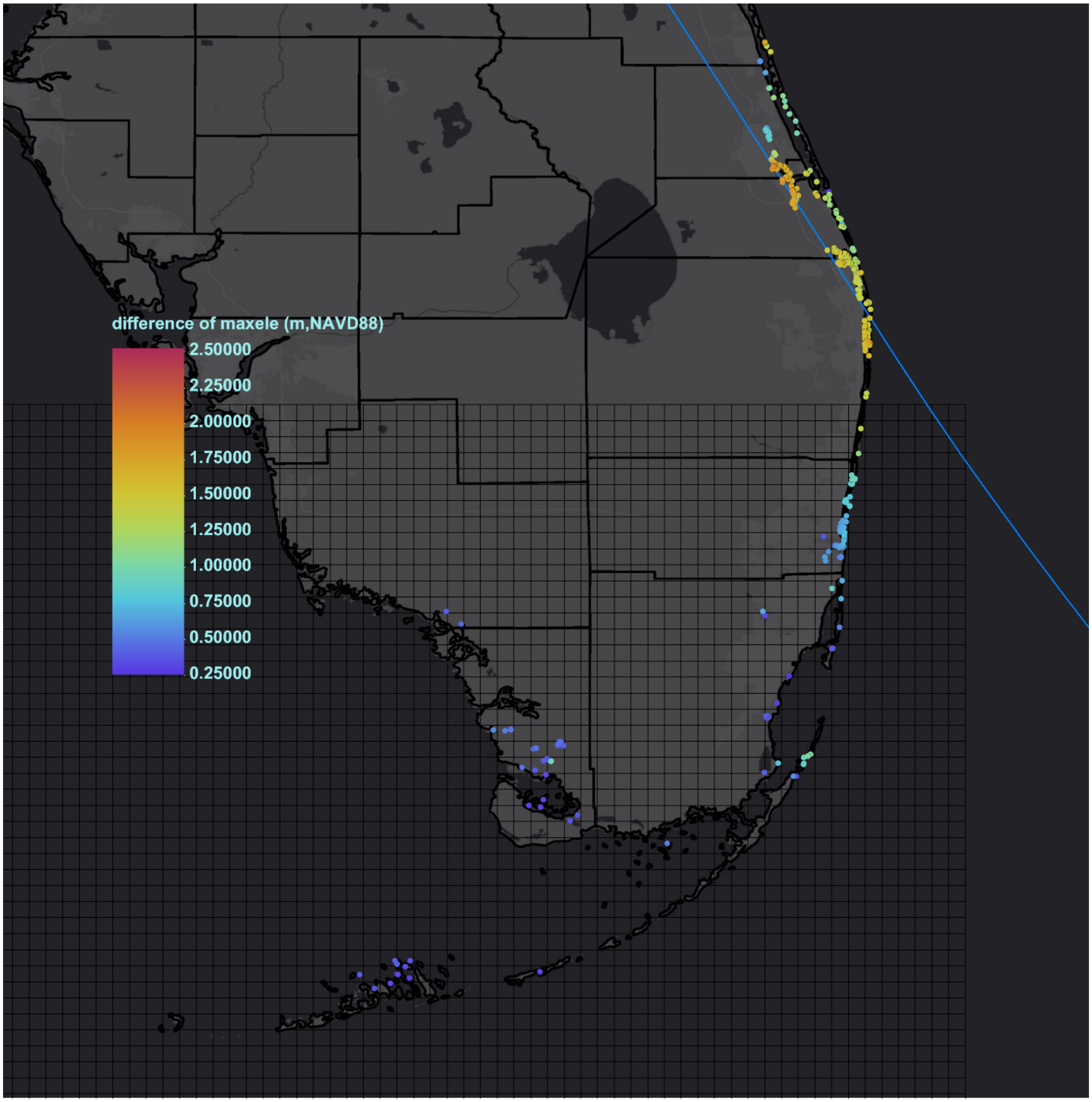

Figure 10. Maximum Water Surface Elevation Difference (meters) between fine and coarse wind and pressure grid for Storm 18 – Fine grid footprint shown for reference

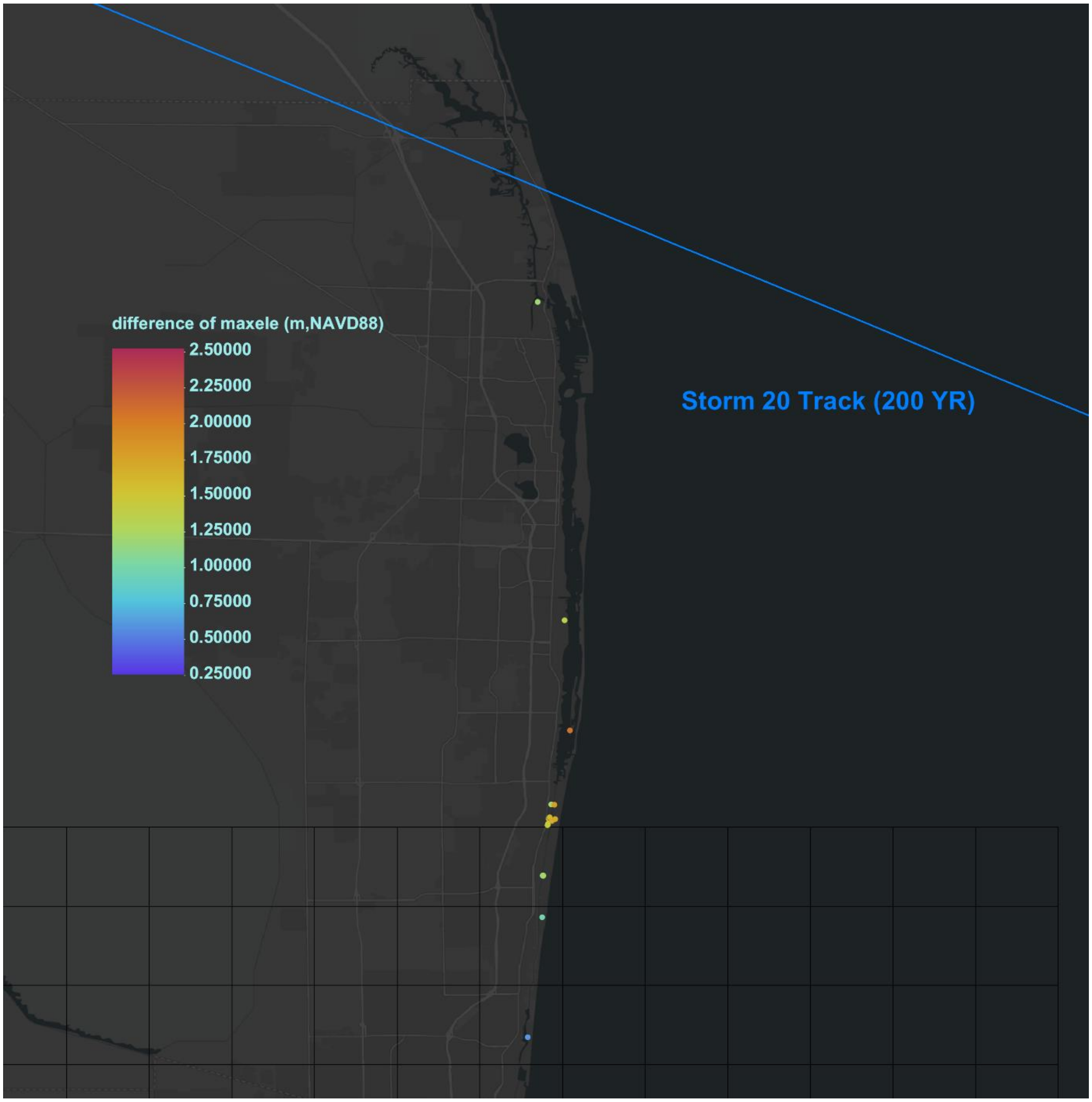

Figure 11. Maximum Water Surface Elevation Difference (meters) between fine and coarse wind and pressure grid for Storm 20 – Fine grid footprint shown for reference

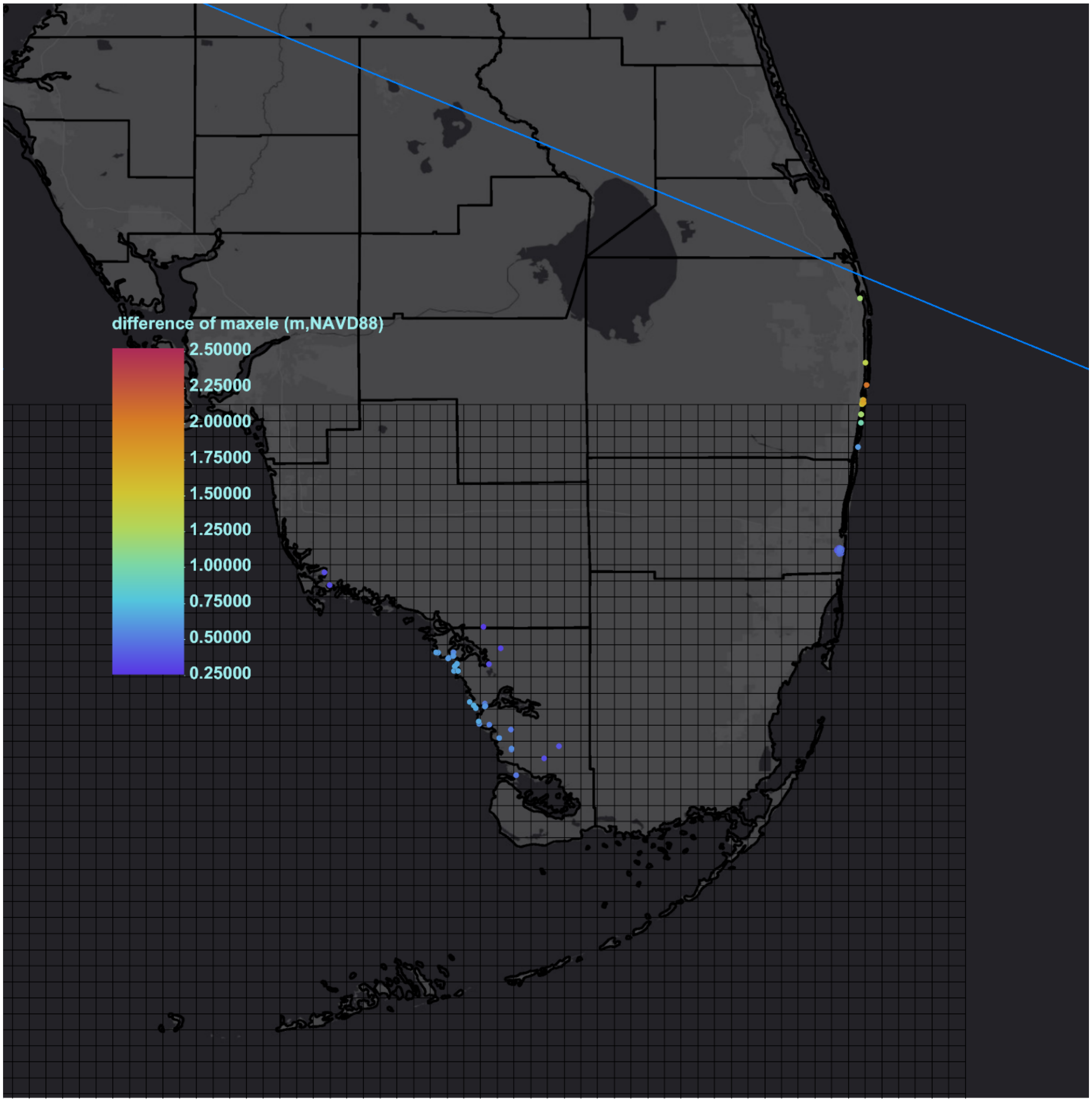

Figure 12. Maximum Water Surface Elevation Difference (meters) between fine and coarse wind and pressure grid for Storm 20 – Fine grid footprint shown for reference

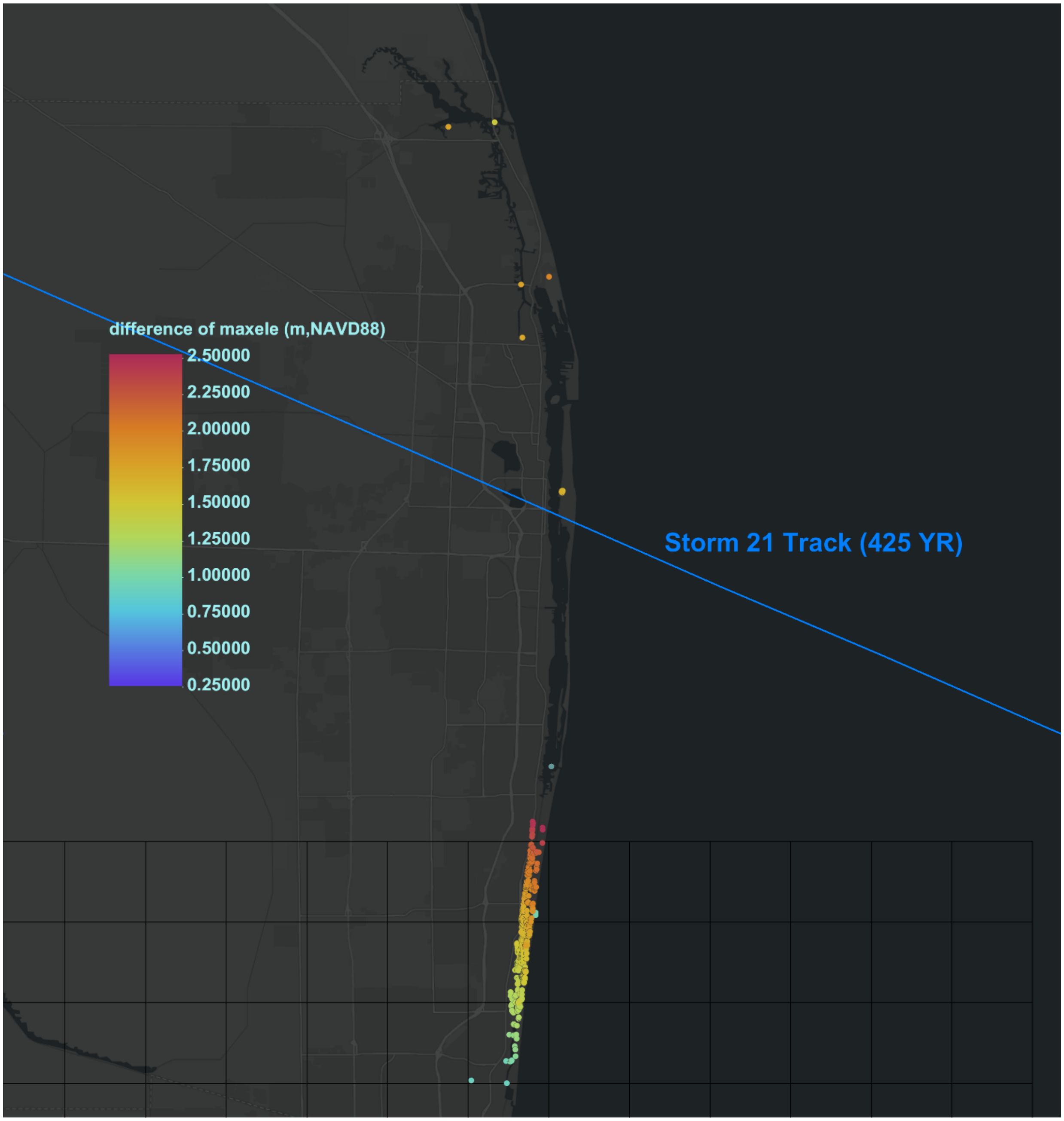

Figure 13. Maximum Water Surface Elevation Difference (meters) between fine and coarse wind and pressure grid for Storm 21 – Fine grid footprint shown for reference

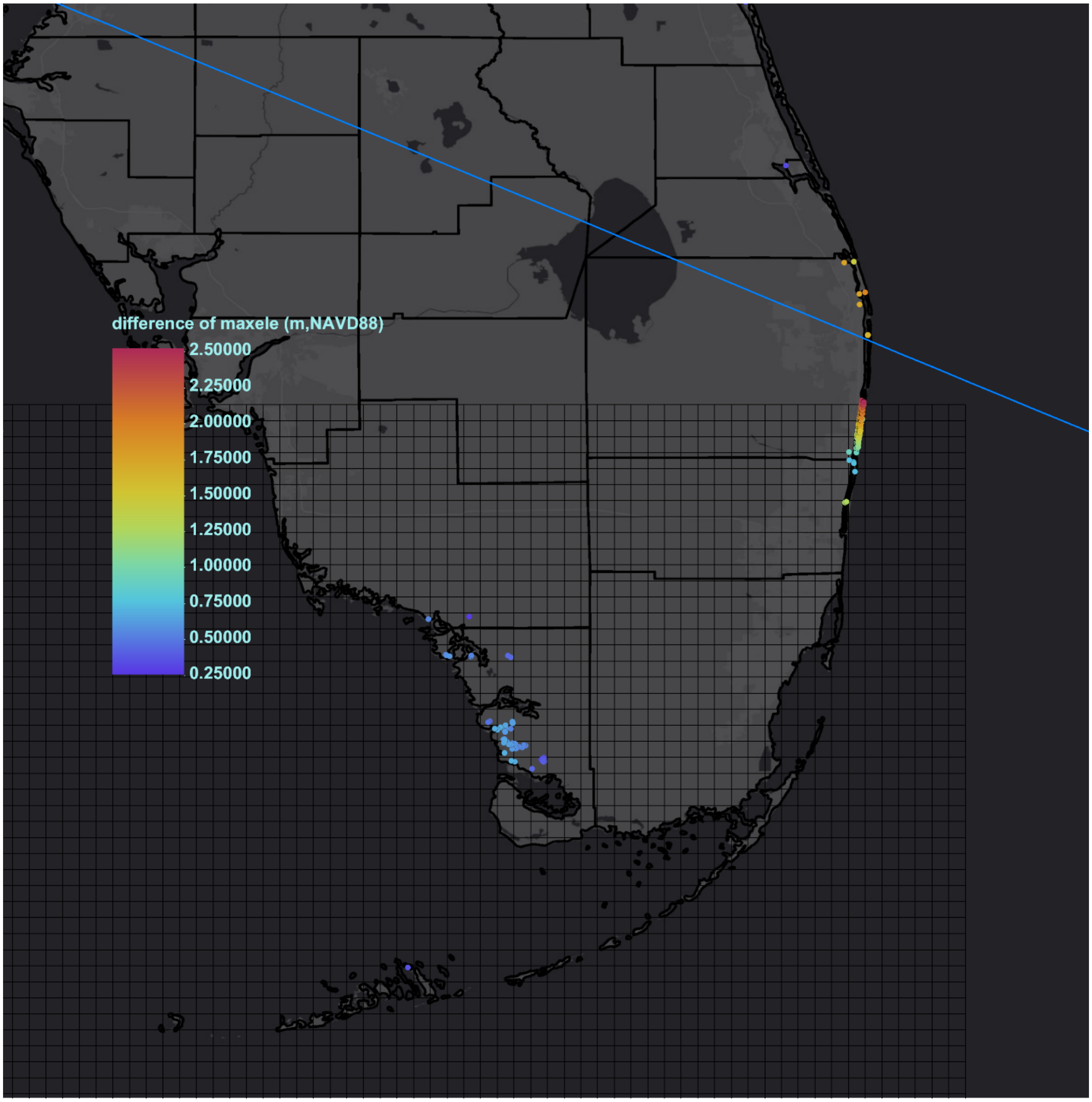

Figure 14. Maximum Water Surface Elevation Difference (meters) between fine and coarse wind and pressure grid for Storm 21 – Fine grid footprint shown for reference

The use of a coarse wind and pressure grid results in differences up to 2.5 meters (over 8 feet) for Storm 21. As expected, the differences are the greatest in the area where the finer grid was used by FEMA. To quantify the impact to the 100-year Stillwater Elevation (SWE), all production events would have to be re-run and statistics recomputed. This was not possible during the 90-day appeal period, but the analyses presented here are sufficient to show that the lack of a detailed wind and pressure grid has a significant impact on model results.

Why Alternative Methods and Data Are More Correct

The modeling completed by the County shows that wind and pressure modeled using inadequate resolution results in differences in WSE of up to 8-feet when compared to results with a finer gird. Based on these results, it is imperative that FEMA obtain wind and pressure data at the finer resolution used for the rest of the SFL Study for the northern portion of Palm Beach County and rerun the analysis.

A review of a several recent available studies completed by FEMA shows that a fine wind a pressure grid covering the entire study area was used. **Table 2** summarizes the studies and the grid sizes used.

Table 2. Wind and Pressure Grid Resolution of Recent FEMA Studies

Study	Basin Grid Resolution	Regional Grid Resolution
FEMA Region 2 NY	0.25 ° (degrees)	0.025 °
FEMA Region 6 LA	0.05 °	0.05 °
FEMA Region 6 TX	0.2 °	0.08/0.02 °
FEMA Region 4 FL, ECCFL	0.25 °	0.05 ° (*)
FEMA Region 4 FL, SFL	0.25 °	0.05 ° (*)

(*) Brevard County (ECCFL) is partially covered, Palm Beach County (SFL) is partially covered

4.2 Model setup does not produce consistently stable results

The SWAN+ADCIRC model requires a model mesh and nodal attributes that sufficiently represents bathymetric, topographic, and land cover features within the study area. Mesh resolution and its distribution should be a function of the hydrodynamics to be simulated. If the mesh has not been created or edited to be numerically stable, the model runs will be inconsistent, and the results will not be reliable.

In the IDS3: Section 1 Production Runs Report Appendix A (FEMA 2018), FEMA describes the instabilities encountered during the productions runs, and the approaches applied to resolve these instabilities. This report will be referred to as FEMA's report in this section.

FEMA encountered several model instabilities summarized as below:

- Instabilities related to wetting/drying (e.g., artificial propagation of the surge wave, nuisance flooding)
- Instabilities related to oblique forward velocities (e.g., in the case of West storms exiting East, storm track/landfall close to parallel with shoreline – not perpendicular)
- Instabilities due to lack of resolution to model hydrodynamics near the Caribbean islands

FEMA's report lists other potential solutions that were failed to improve model stability as:

- Decreasing spatially variable tau0 base values to numerically correct instabilities near the Caribbean islands
- Increasing Manning's n coefficient to 0.15 to dampen instabilities via higher bottom friction near Caribbean shorelines
- Changing SWAN time step from 20 minutes to 10 minutes to increase the frequency of the wave coupling
- Decreasing H0 to dampen unrealistic wetting
- Decreasing HABSMIN (within the SWAN+ADCIRC wetting and drying algorithm directly) to further restrict wetting
- Deactivating the NOFF array through the fort.15 &wetDryControl namelist to turn off elemental wetting and drying, which could theoretically encourage nodes to dry more quickly depending on the element's water surface elevation slope

Finally, FEMA applied the following approaches to resolve the instabilities described above by:

- Restricting localized water level gradient by applying elemental slope limiter (ESL) nodal attributes.
- Canal filling
- Disabling wind stress forcing locally
- Deepening of the Caribbean bathymetry

These approaches are described and commented on below.

Restricting Localized Water Level Gradient

FEMA's report states: "Overall, 376 out of 392 storm simulations applied elemental slope limiter (ESL). The team developed eleven versions of ESL datasets, titled ESL-v1 through ESL-v11. Production simulations ultimately did not use all eleven datasets. Each time a production run displayed a hot spot in a new location, the team expanded the ESL dataset by adding in the new nodes. Several hot spots appeared repeatedly throughout production simulations, so expanding rather than replacing the previous ESL dataset allowed future runs to benefit from previously corrected hot spots."

Ideally, a well-established model mesh and nodal attributes should not require the application of the ESL nodal attribute. FEMA's report indicates that ESL dataset was expanded by adding new nodes as the instabilities occurred. The report states: "ESL datasets included between 7,000 and 33,500 nodes out of 2.25 million in the SFLSSS model mesh." and "Production simulations did not use all eleven datasets". FEMA used 8 different versions of the ESL datasets.

FEMA defined ESL nodal attributes at two locations within Palm Beach County near the northern and southern ends of the Lake Worth Lagoon as shown in **Figure 15**. The model nodes where localized gradients were specified are indicated by the blue and purple dots.

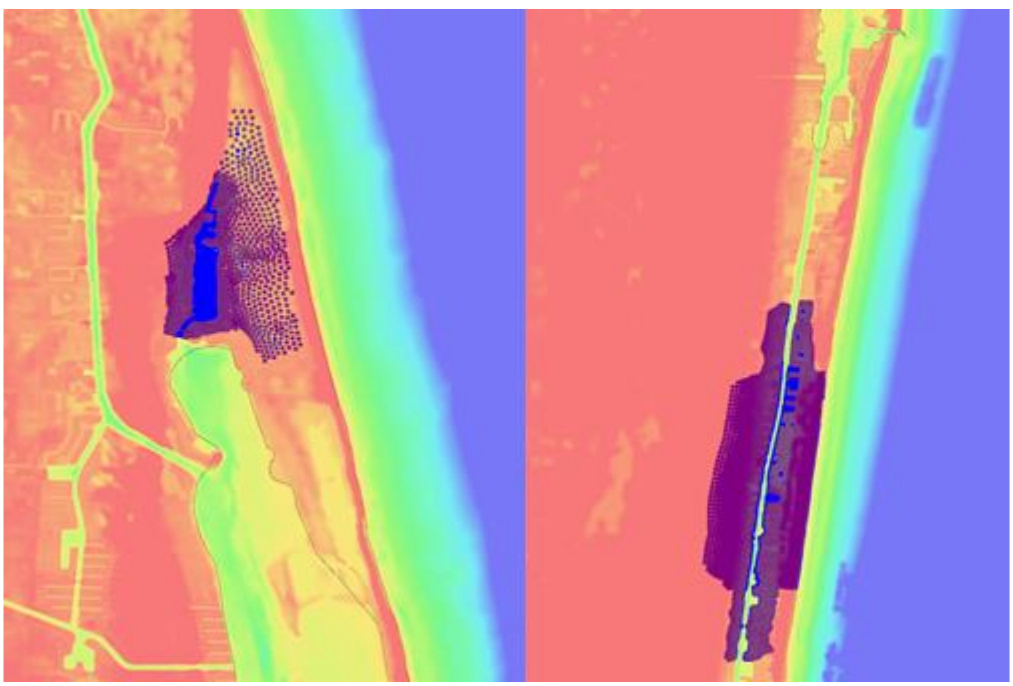

Figure 15. Model Instabilities – Restricted Localized Water Level Gradients

Canal Filled Mesh

The FEMA report states: "In its post-simulation reviews, the production run review team noted many instabilities in or adjacent to narrow navigation or SFWMD water control canals. The mesh contains many canals less than 150 ft wide; in some locations, the mesh captures canals as narrow as 30 ft (see IDS1, Section 7). The SWFLSSS found that narrow canals often invoked instabilities. As a solution, the SWFLSSS team artificially "filled in" problematic canals for certain production simulations by raising nodes falling inside the channel banks to a constant, dry elevation (with global initial water level at mean sea level). Effectively removing certain canals narrower than 120 ft from the mesh by raising their node elevations to +3 ft-NAVD (at or below the bank elevation)." (Note: SWFLSSS refers to the Southwest Florida Storm Surge Study).

Disabled Wind Stress Forcing in Broward County

FEMA disabled wind stress forcing in select overland locations to allow the wetting front to propagate solely through local hydrodynamics. Palm Beach County did not review the impacts of this application on model results in the County.

Deepening of the Caribbean bathymetry

FEMA report states: "fatal instabilities in the Caribbean were resolved by disabling wind stress near the shorelines of Cuba and Bahamian islands. The team further eliminated instabilities in shallow areas of the Caribbean by artificially deepening nodes near the shorelines of Cuba and the Bahamas. This group of mesh changes occurred at least 90 miles from the project area." Palm Beach County did not review the impacts of this application on model results in the County.

Identifying Instabilities

FEMA's report states: "The team first verified results which truly constituted instabilities or numerically-induced water masses rather than anomalous, yet reasonable, water levels. Difficult to drain areas serve as examples that sometimes yielded unrealistic results yet at other times yielded reasonable results. Because the SWAN+ADCIRC production run phase of the project did not model hydrology or stormwater drainage, gravity and offshore winds served as the only means for a surge wave to recede. If the topography did not support surge recession, then the team could potentially accept the area remaining inundated throughout the rest of the simulation. If the inundated area remained static and did not drain, the team classified simulation as stable. If the inundated area featured an unrealistically propagating wetting front, or unrealistically escalating water levels, the team classified the simulation as unstable."

The description from FEMA on what a numerically unstable model run is vague. It is perfectly reasonable for an area to remain "statically" dried after a powerful storm. Generally, ADCIRC, non-fatal instabilities can be identified by looking at anomalous maximum velocities. It is also possible to use non-fatal error override (NFOVER) option in ADCIRC. FEMA uses 1 for this parameter. ADCIRC documentation explains this option and its potential uses as:

NFOVER = non-fatal error override option;

= 0, inconsistent input parameters will cause program termination.

= 1, inconsistent input parameters will, (when possible), be automatically corrected to a default or consistent value and execution continued. Be sure to read the nonfatal warning messages to see whether any parameters have been modified. Note that not all inconsistent parameters can be corrected automatically and therefore fatal error messages and program termination may still result.

Note for NFOVER:

Occasionally, the elevation solution becomes unphysically large due to improper numerical parameter settings, time step stability criteria violation. It can be useful for ADCIRC to terminate based on a user-specific limit to the computed water elevation. To enable this feature, ADCIRC must be compiled with the DEBUG_WARN_ELEV compiler directive. This is set in the cmplrflags.mk file. For example, for the serial model,

DA := -DREAL8 -DLINUX -DCSCA –DDEBUG_WARN_ELEV

and for the parallel model:

DP := -DREAL8 -DLINUX -DCSCA -DCMPI -DDEBUG_WARN_ELEV

This enables extra parameters in the fort.15 file, specified on the NFOVER line:

NFOVER, WarnElev, iWarnElevDump, WarnElevDumpLimit, ErrorElev

ADCIRC then monitors the maximum water elevation and behaves as follows:

A warning is issued if the elevation exceeds WarnElev.

A global elevation file (written to fort.69) will be written if WarnElev is exceeded AND iWarnElevDump == 1

Execution will be terminated if WarnElevDumpLimit global elevation files have been written due to the above warning limits.

Execution will be terminated if elevation exceeds ErrorElev.

SFLSS simulates 392 storms in a large and complex domain. It is not feasible to identify instabilities based on vague descriptions of what instabilities are. ADCIRC provides the tools to identify potential numerical instabilities which were not used by FEMA.

Lack of Quality Assurance/Quality Control (QA/QC) at local level

Some of the approaches discussed above that were employed by FEMA are routine and customary for numerical models if it is demonstrated that they do not alter the hydrodynamic and coastal flooding processes elsewhere within the study area.

FEMA's report indicates several times that the sensitivity to the changes made to the meshes and nodal attributes were examined at a regional scale.

- "The team also conducted sensitivity testing to examine effects of model mesh and nodal attribute changes to regional maximum water levels"
- "Any potential solution may induce small, localized changes in maximum water level that are not practical to trace, so the team focused on regional-scale changes."
- "Fortunately, several model mesh and parameter changes did alleviate instabilities without affecting regional-scale results."

As an example of mesh edits, mesh filling by FEMA in canals within Palm Beach County along the Loxahatchee River and ICWW in Jupiter and Tequesta are shown in **Figure 16**. 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 (Figure copied from FEMA 2018).

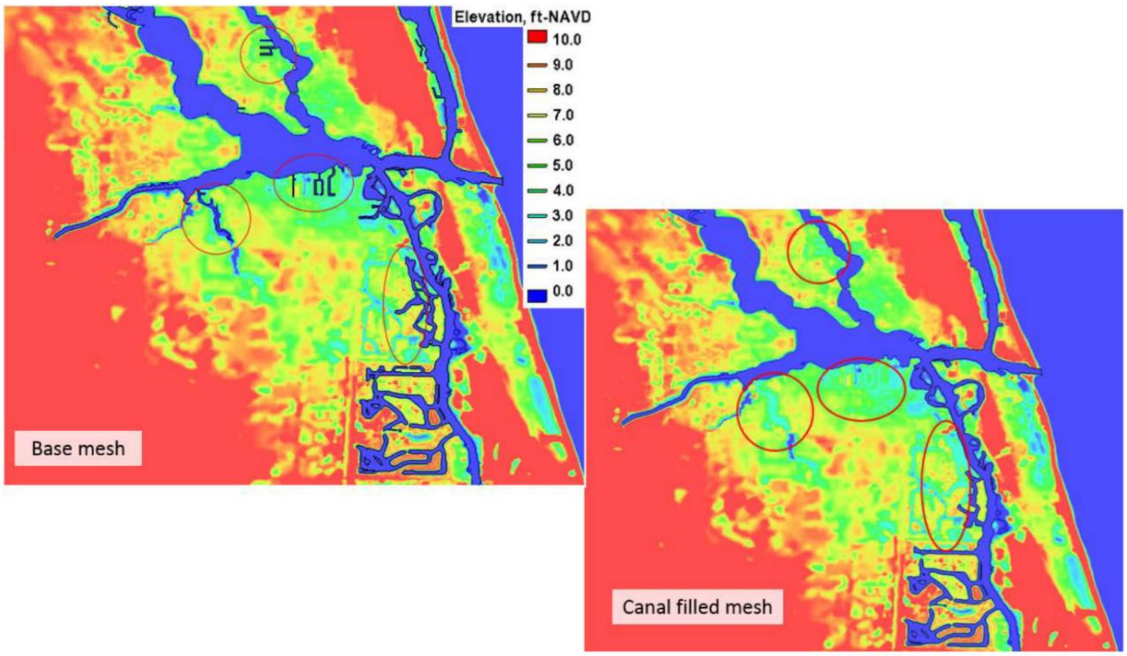

Figure A.11. Base Mesh vs. Canal Filled Mesh Node Elevations in Narrow Canals, Palm Beach County

Figure 16. Filled Canals in Palm Beach County

FEMA report states: "filling the shorter narrow canals in Palm Beach County and Miami-Dade County did not induce regional differences in maximum water surface elevation. Figure A.16 (**Figure 17**) shows a difference plot of maximum water level for storm 65, which made landfall in Boca Raton and produced significant surge throughout coastal Palm Beach County. The prevalence of green contours indicates minor influence of the canal filled mesh on regional-scale maximum water levels."

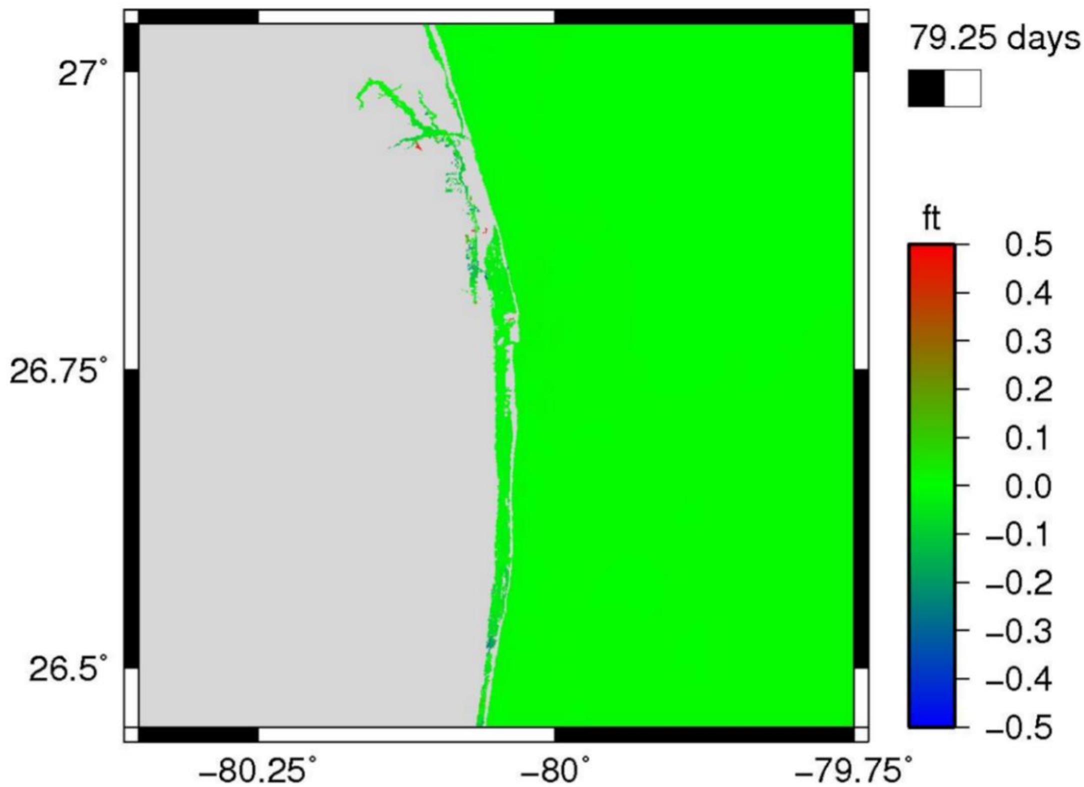

Figure A.16. Palm Beach County, Storm 65, Max Water Level Difference [Base Mesh - Canal Filled Mesh] (ft)

Figure 17. Max Water Level Difference Storm 65 (Figure A.16 from FEMA Report)

Figure 17 indicates minor influence of the canal filled mesh on regional scale maximum water levels. However, FEMA does not ask nor answer the question why canals filled at the north end of the County have a local impact near Boynton Inlet (a drop in WSE of ~0.5 feet can be seen) 30 miles away from the canal fills. Numerical instabilities often present themselves on a single node which may or may not be visible/significant from a regional point of view. Similarly, a completed run does not necessarily mean a stable run. Prevalence of the “green color” cannot be considered as a scientific quantification to conclude that the changes made to the mesh and the nodal attributes have no impact on model results on local level at which the findings of the study are applied to drive FIRMs. Furthermore, FEMA states that “storm 65, made landfall in Boca Raton and produced significant surge throughout coastal Palm Beach County”. Storm 65 was identified to generate WSEs equivalent to only 30 years return period near Boynton Inlet. The impacts should have been investigated and presented using multiple storms representing different return period intervals.

Importance of consistent model setups in producing reliable results

FEMA used 24 unique combinations of different meshes and nodal attributes to complete model runs for 392 storms used for the study (FEMA 2018). **Figure 18** shows the max WSE simulated by FEMA in Palm Beach County per Storm id bins of 20. Simulated maximum elevations from all production runs were extracted and the storm responsible for creating the maximum WSE elevation were plotted at each node with a unique color for each bin. The numbers seen on each storm bin indicates the number of unique combinations of mesh and nodal attributes used to be able to complete the runs in that area. In Palm Beach County, FEMA used 7 to 11 unique combinations within any given area as indicated in **Figure 18**.

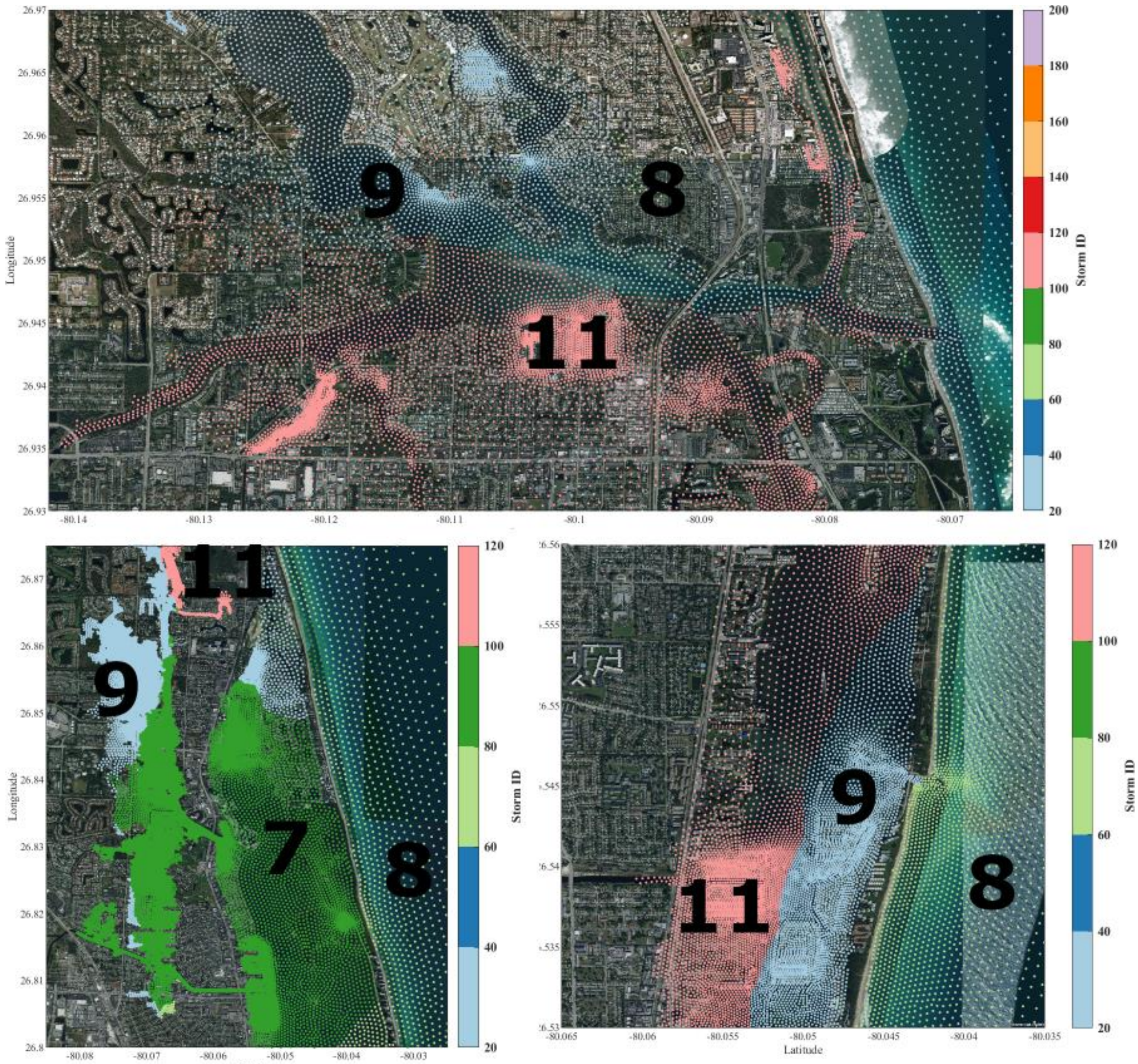

Figure 18. Max elevation Storm ids and mesh/nodal attributes combinations used for each group.

For instance, the maximum water surface elevations near Boynton Inlet area are results of models for Storms 20 through 40. FEMA used 9 unique combinations of mesh and nodal attributes to complete 20 synthetic storm runs in this area (**Table 3**). The County acknowledges the need to edit meshes and nodal attributes to achieve stable model results. However, this practice should converge to a single mesh and a single nodal attributes file that will be used for the entirety of the SFL Study. Otherwise, every single combination used (total 24) needs to be cross checked against each other, which is not feasible and was not carried out by FEMA.

Table 3. Mesh and Nodal Attributes Applied in Final Storm Run from the FEMA report - Full Table in Appendix A

Storm	Track	Mesh Description	SCC (surface canopy coefficient)	ESL (elemental slope limiter)	MN (manning's N)
20	**JPM_30002006**	**canal filled**	**v3**	**v5**	**canal filled edit**
21	JPM_30002007	canal filled	v3	v5	canal filled edit
22	**JPM_30002008**	**canal filled**	**v3**	**v6**	**canal filled edit**
23	JPM_30002009	canal filled	v3	v5	canal filled edit
24	**JPM_30002010**	**canal filled+ deepened_Carib_v2**	**v3**	**v6**	**canal filled edit**
25	**JPM_30002011**	**canal filled+ deepened_Carib_v2**	**v3+Everglades+ CoralGables**	**v9**	**canal filled edit**
26	**JPM_30002012**	**canal filled+ deepened_Carib_v2**	**v3+Everglades**	**v7**	**canal filled edit**
27	JPM_30002013	canal filled+ deepened_Carib_v2	v3+Everglades	v7	canal filled edit
28	**JPM_30002014**	**canal filled**	**v3+Everglades**	**v6**	**canal filled edit**
29	JPM_30002015	canal filled	v3+Everglades	v6	canal filled edit
30	**JPM_30002016**	**canal filled**	**v3+Everglades**	**v5**	**canal filled edit**
31	**JPM_30002017**	**base**	**CCAP**	**v2**	**base**
32	**JPM_30002018**	**base**	**CCAP**	**none**	**base**
33	JPM_30002019	base	CCAP	v2	base
34	JPM_30002020	base	CCAP	v2	base
35	JPM_30002021	base	CCAP	v2	base
36	JPM_30002022	base	CCAP	v2	base
37	JPM_30002023	base	CCAP	none	base
38	JPM_30002024	base	CCAP	v2	base
39	JPM_30003025	base	CCAP	v2	base
40	JPM_30003026	base	CCAP	v2	base

Local numerical instabilities at PBC inlets

FEMA reported that the model mesh developed for the SFL Study provided sufficient resolution to "include 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 locations and are discussed below.

- <u>Boynton Inlet</u>: 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 feet, NAVD88), rapid drawdown of the WSE within the inlet (-10 feet, NAVD88), and then the rapid rise to match the WSE within the Atlantic Ocean (+2 feet, NAVD88) as shown by the red dashed circle in **Figure 19**. The WSE changes occurred within 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 (bottom panel in **Figure 19**) in the north jetty at the intersection with the coastline creating an additional hydraulic connection, which does not exist.

There are two sources of error in this kind of modeling: physical representation error and numerical truncation error. Numerical solutions to partial differential equations can be sensitive to the level of spatial resolution. In general, the so-called truncation error decreases as the spatial resolution increases. The rate at which the error decreases depends on the order of the numerical scheme used in implementing the numerical model.

For critical hydraulic features, such as inlets and channels that connect the open ocean to protected waters behind barrier islands, it can be important to ensure that adequate resolution in the cross-channel direction is available so that sufficient flux passes through.

It is generally accepted as good practice to ensure that a few model nodes span the width of a tidal inlet, particularly when the bathymetry exhibits a convergent characteristic, as does Boynton Inlet on the ocean end of the channel.

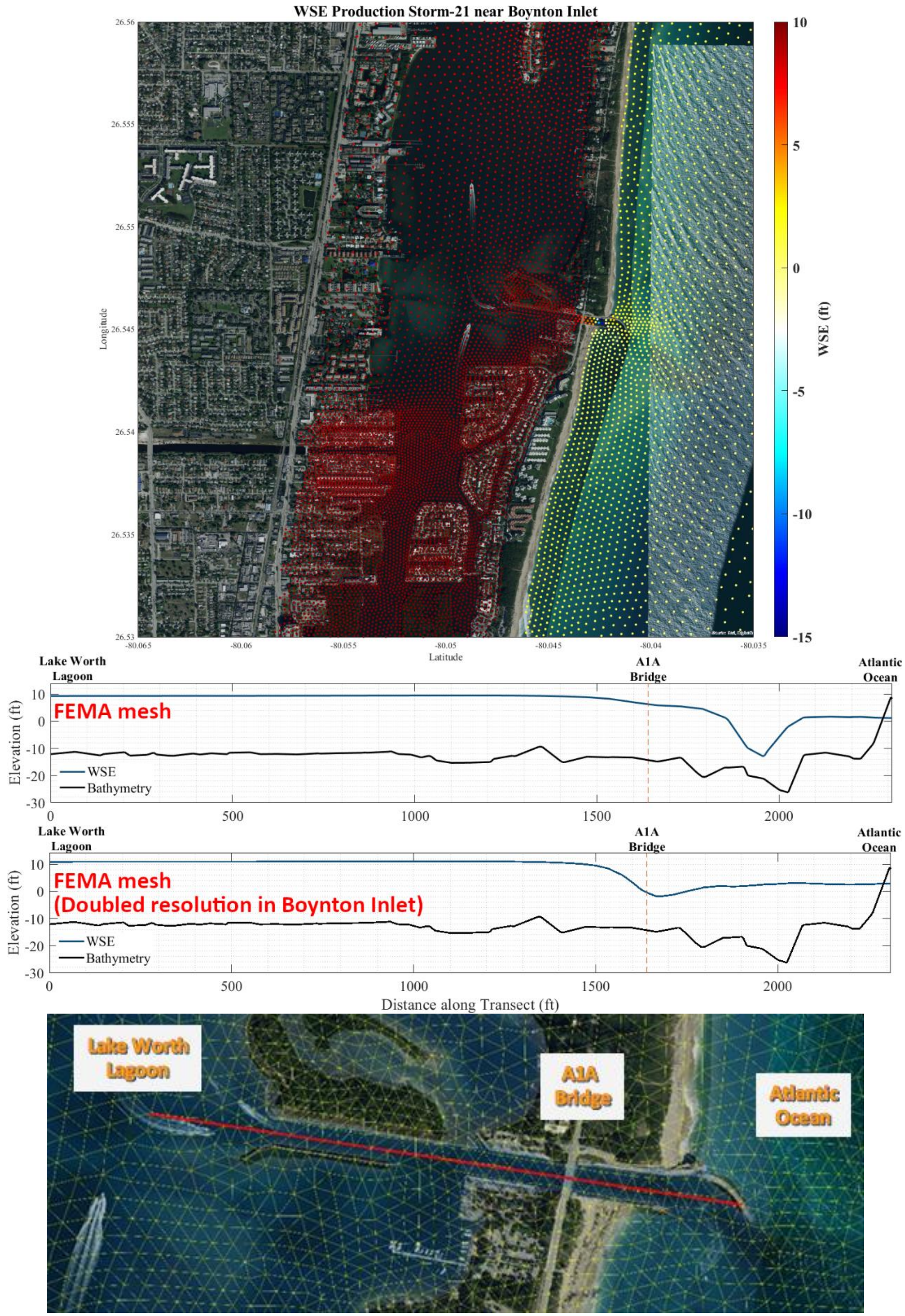

Figure 19. Water Surface Elevation – Boynton Inlet – Synthetic Storm 21 (FEMA mesh vs Double resolution at Boynton Inlet)

The basic resolution test of Boynton Inlet (the doubled resolution Boynton Inlet grid) indicates that two nodes (one cross-channel element edge) does not adequately resolve the complex hydraulic nature of the inlet. When increasing the resolution in the area, the water surface elevation difference in the along-channel direction decreases significantly (as compared to the solution on the FEMA grid), indicating that the FEMA grid resolution is not sufficient to ensure the computed water level solution is adequately resolved. Ideally, a "convergence" experiment would have revealed to FEMA that the computed solution changes significantly when the resolution is doubled. The doubled resolution test indicates that FEMA solution is not yet adequately resolved in the Boynton Inlet area. It should be noted that the resolution in other inlets in the region (e.g., Palm Beach Inlet) are much better resolved compared to Boynton Inlet. **Figure 20** shows that the hydraulic jump at Boynton Inlet was visible in FEMA's QA/QC plot for Boynton Inlet.

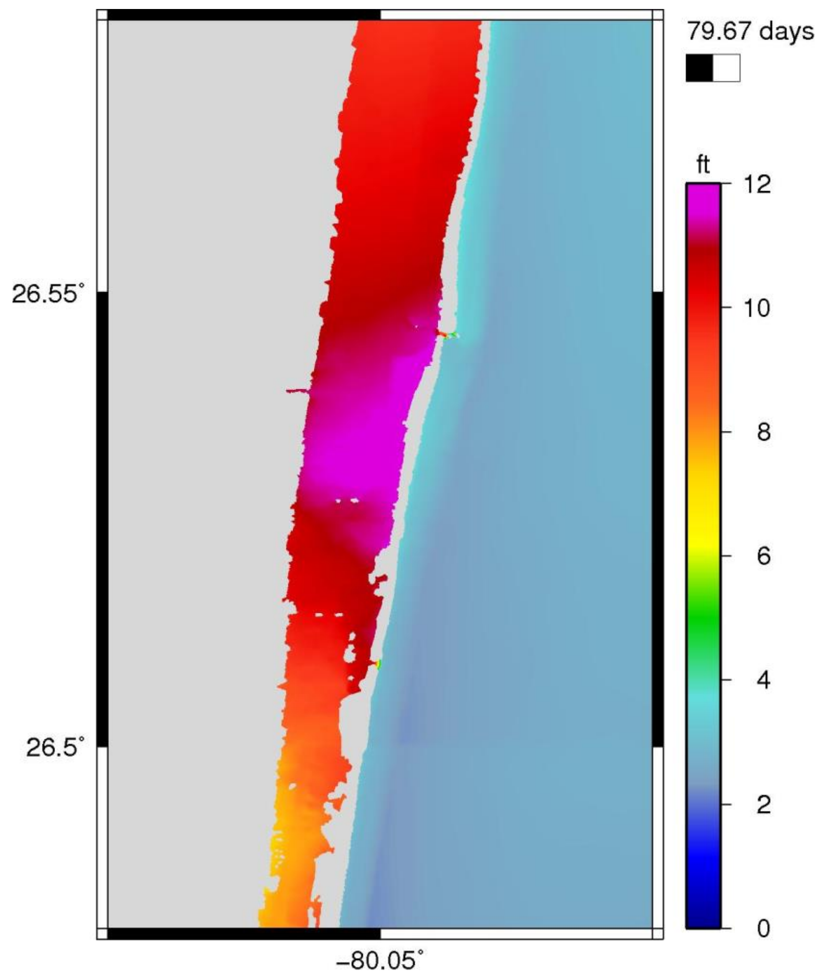

Figure 20. Maximum WSE produced (Storm-21) for QA/QC purposes by FEMA south Palm Beach County – Near Boynton Inlet. (Source: FEMA 2018)

Assignment of Nodal Attributes

The SWAN+ADCIRC model accounts for the effect of topographic and vegetation features through the nodal attribute input file (or fort.13 file). This input file allows model parameter definition on a node-by-node basis to account for spatial variation in the parameter values. SWAN+ADCIRC model parameters that can receive values in the fort.13 file include

- Surface directional effective roughness length
- Surface canopy coefficient
- Manning's n coefficient at the sea floor
- Sea surface height above geoid
- Average horizontal eddy viscosity in sea water
- Primitive weighting in continuity equation parameters

Here, the County focuses on the use of Manning's n coefficient values as derived from the updated 2010 Coastal Change Analysis Program (C-CAP) data coverage.

"The SWAN+ADCIRC model applies values of Manning's n at the sea floor to account for hydraulic roughness in wet areas of the model domain. Notably, as storm surge inundates upland areas, initially dry topographic areas become wet and require Manning's n values in the model. Therefore, the stated parameter name proves somewhat misleading as the model requires Manning's n values at all nodes. The ADCIRC model component converts Manning's n values to an equivalent quadratic friction coefficient before the model calculates bottom stress. The ADCIRC model incorporates the bottom stress as a resistance to flow in the depth-averaged momentum equations (Luettich et. al, 1992)."

For Manning's n, the nodal attribute file (fort.13) contains a default value, and a list of nodes where the user defines the Manning's n values. In common practice, the list of nodes provided by the modeler are land nodes where the values are interpolated from a land cover database while the default value represents the water nodes (a commonly used value is n=0.02, as in the case of SFLSSS).

In this study, FEMA assigned 2,095,907 nodes with Manning's n values interpolated from the 2010 C-CAP land cover database and used a default value of n=0.1 on the remaining 153,186 nodes (n=0.01 is the C-CAP suggested value for Mixed Forest / Palustrine Forested Wetland).

Figure 21 through **Figure 23** shows the FEMA's assigned Manning's n values throughout the entire study area, for Palm Beach County and near Boynton Inlet respectively. **Figure 25** shows the land and water nodes using the default Manning's n values (0.1) assigned by FEMA.

In **Figure 23**, it can be observed that the mouth of Boynton Inlet is covered with Manning's n value of 0.05 (Classified as scrub/shrub/wetlands). This is most likely caused by the source used to interpolate Manning's n values on to the mesh nodes. 2010 C-CAP Landcover is a coarse dataset, it does not resolve all narrow channels and inlets (**Figure 24**). It appears a modification to the Manning's n values was carried out in the lagoon side of the Boynton Inlet while the connection to the ocean was "blocked", "slowed-down" by using Manning's n values used to represents shrubbery and wetlands.

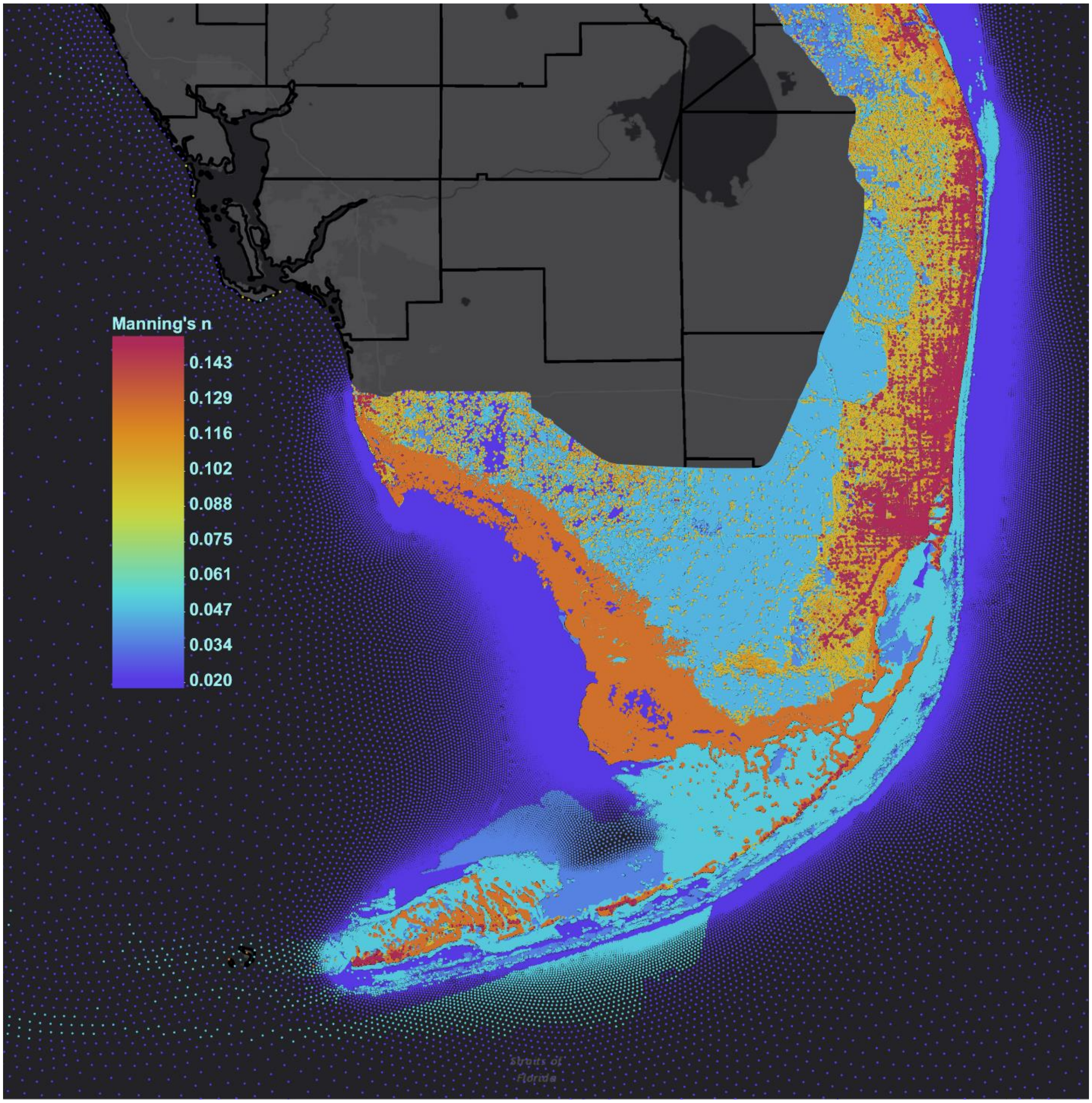

Figure 21. FEMA's assigned Manning's n values (Entire SFL Study area)

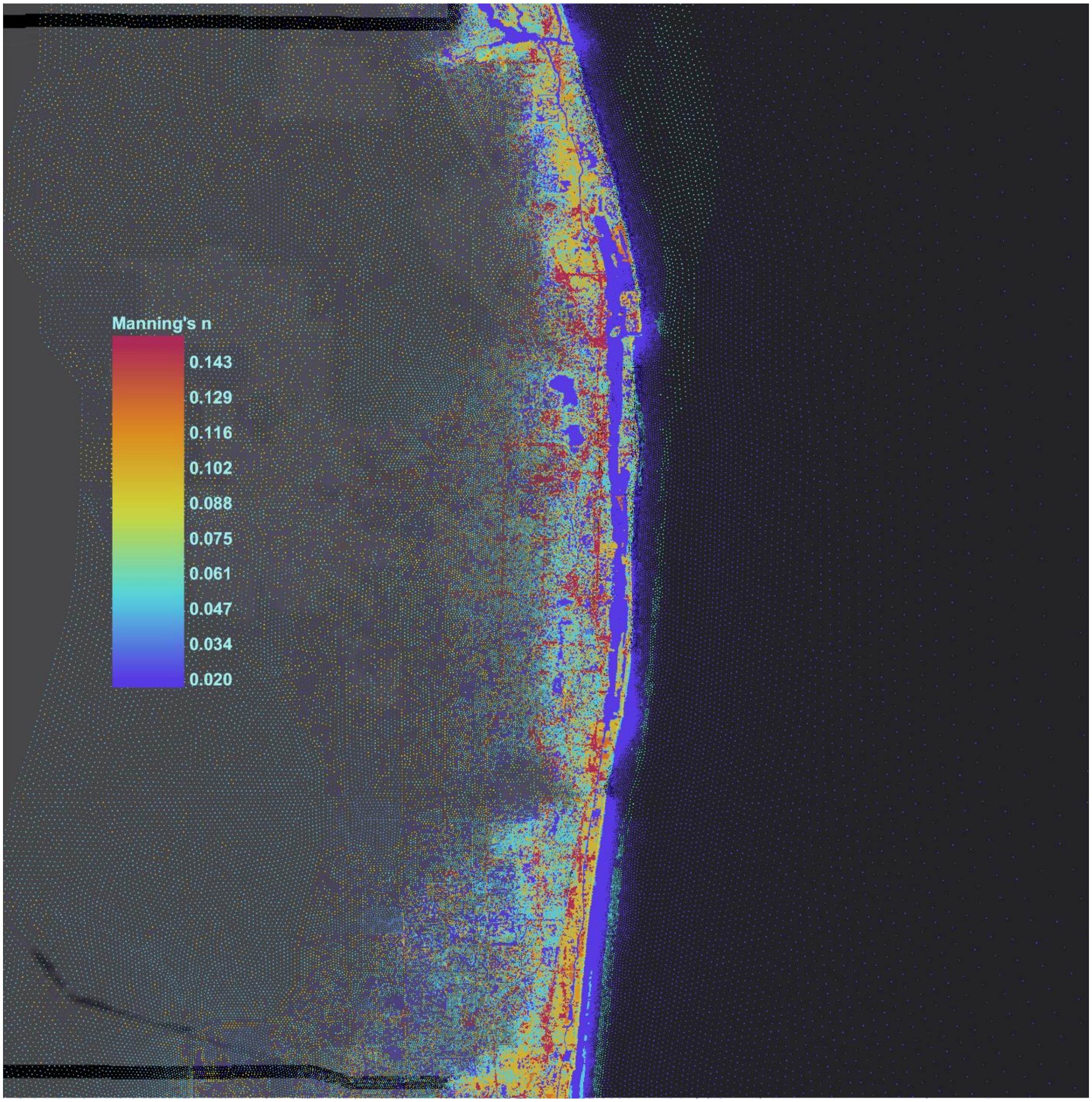

Figure 22. FEMA's assigned Manning's n values (Palm Beach County)

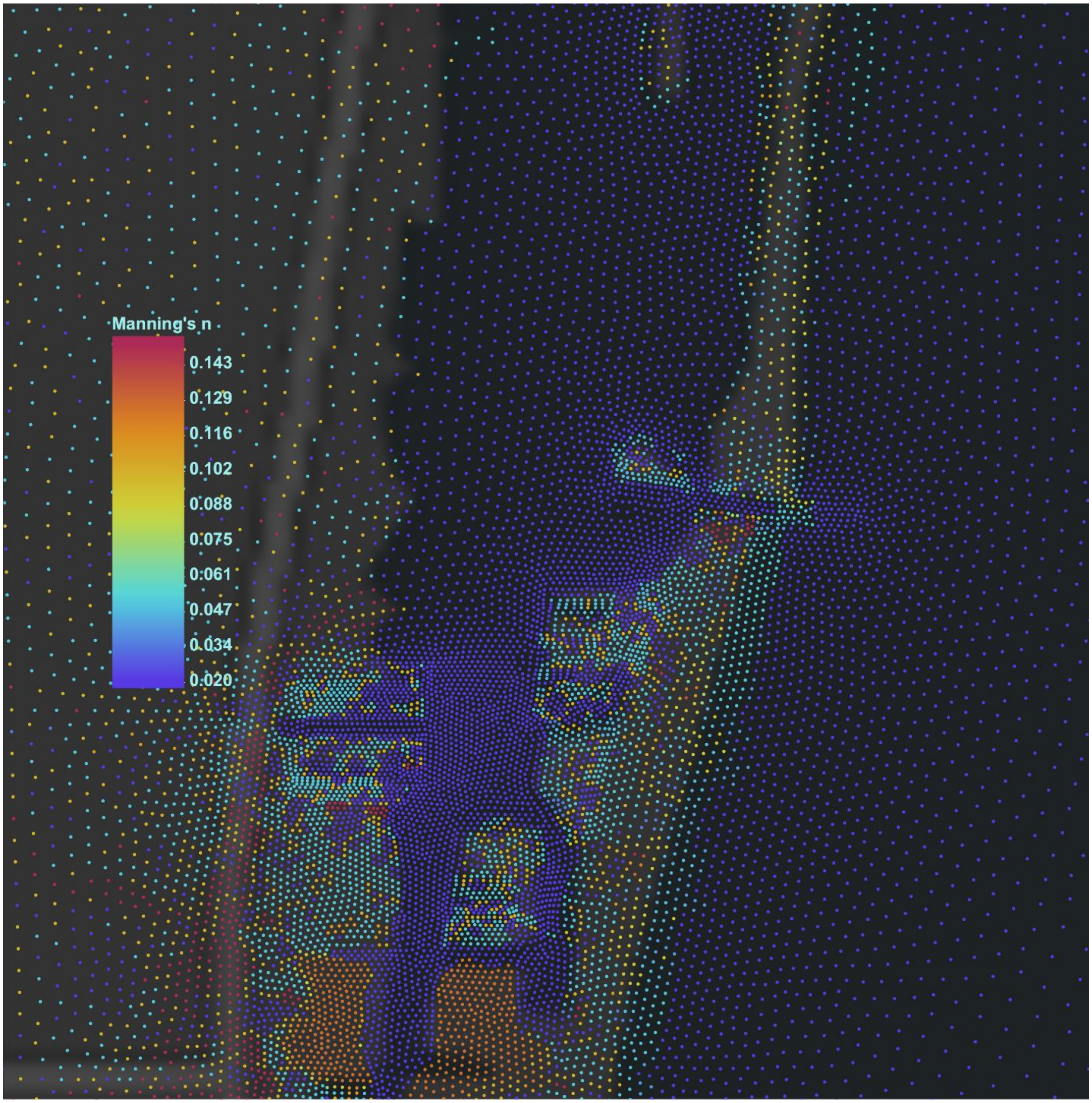

Figure 23. FEMA's assigned Manning's n values (Boynton Inlet)

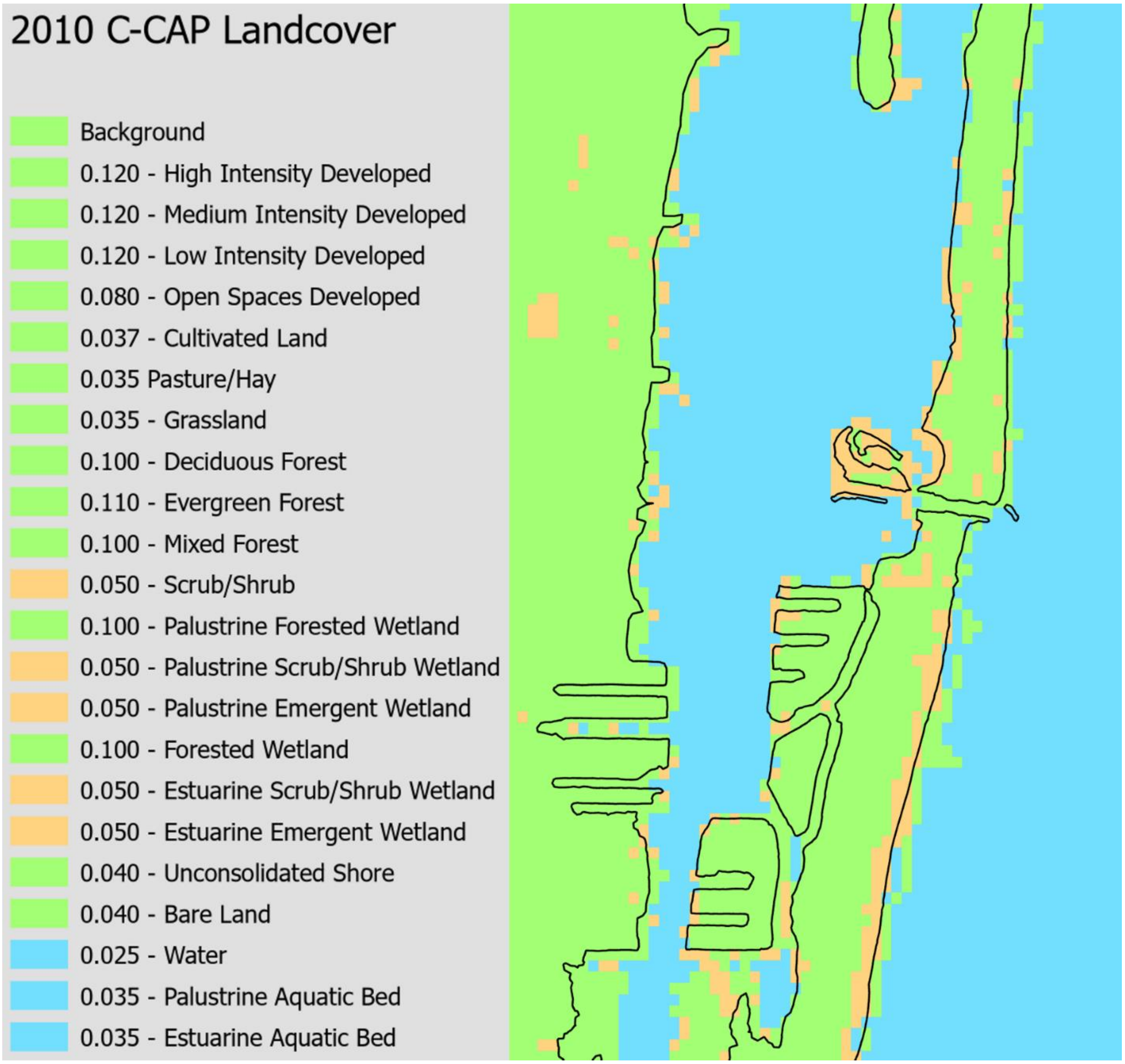

Figure 24. 2010 C-CAP Landcover map simplified – Land classification near Boynton Inlet

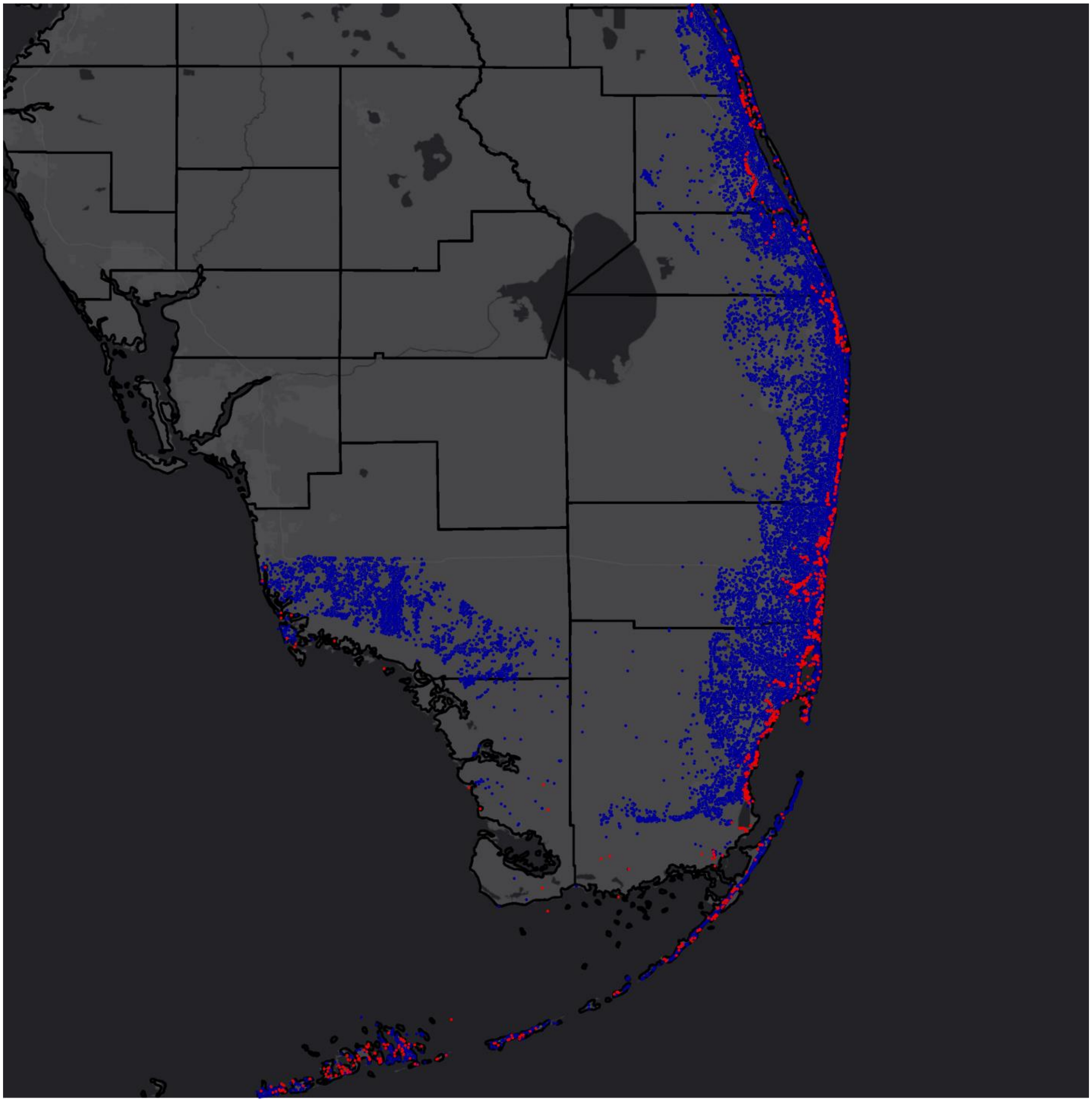

Figure 25. Default Manning's n (0.1) coverage for the entire study area. Red (nodes in canals), Blue (overland).

Figure 25 shows the default Manning's n coverage for the study area. FEMA defined the default Manning's n value of 0.1 in the nodal attributes file (fort.13) used in the study. This is an acceptable approach; however, the assigned default value (0.1) represents forests and wetlands. Therefore, this default value should not be applied to water nodes. Red nodes in **Figure 25** shows where this is not the case for the entire study area whereas **Figure 26** focuses on Palm Beach County.

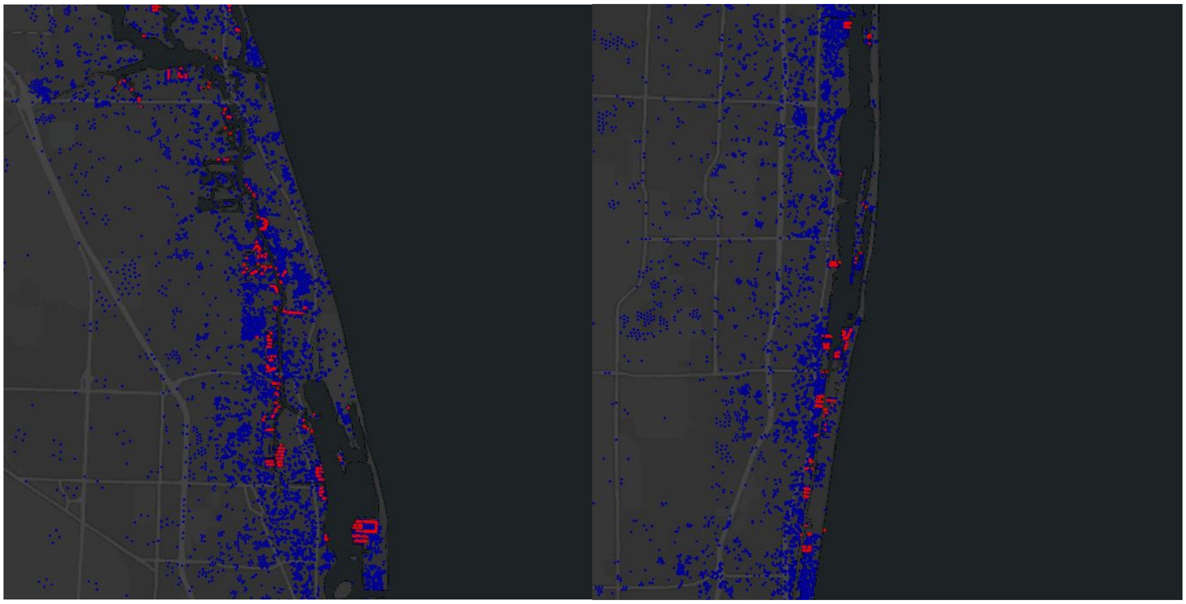

Figure 26. Default Manning's n (0.1) coverage for PBC. Red (nodes in canals), Blue (overland).

The nodes with high Manning's n values represent rougher terrain and have a direct impact on the hydrodynamics calculated on them. It was apparent that some of these nodes were used for numerical stability purposes, however it is not listed or presented as one of the approaches applied to overcome instabilities. The impact of employing high manning values in water nodes was not explored.

Re-simulated storm results with FEMA inputs does not match FEMA's original results
To complete its review and analysis of FEMA's preliminary results, the County re-ran selected storms. The selected storms were re-simulated using the original setup files provided by FEMA. Additionally, reruns were completed using the same source codes for ADCIRC/SWAN (v52.30) as reported by FEMA. FEMA's original maximum elevation results (maxele_400sec.63 files provided by FEMA) were compared to the County's rerun of the same storms. A difference of maximum elevations is also presented for each storm rerun. **Figure 27, Figure 28, and Figure 29** show the results of Storm 18 maximum water elevation results from the County's rerun, maximum water elevation results provided by FEMA and the difference between the two results (Original FEMA results minus County rerun results) respectively.

Similarly, **Figure 30, Figure 31, and Figure 32** show the results for Storm 20. **Figure 33, Figure 34, and Figure 35** show results for Storm 21.

The differences between FEMA's maximum elevation results and the County's reruns are significant. Specifically, storm 20 and storm 21 are on the tail end of the probability distributions ultimately used to calculate BFEs. Even small changes in the results of higher return period events (e.g., storm 20, storm 21) can have a big impact on the final results.

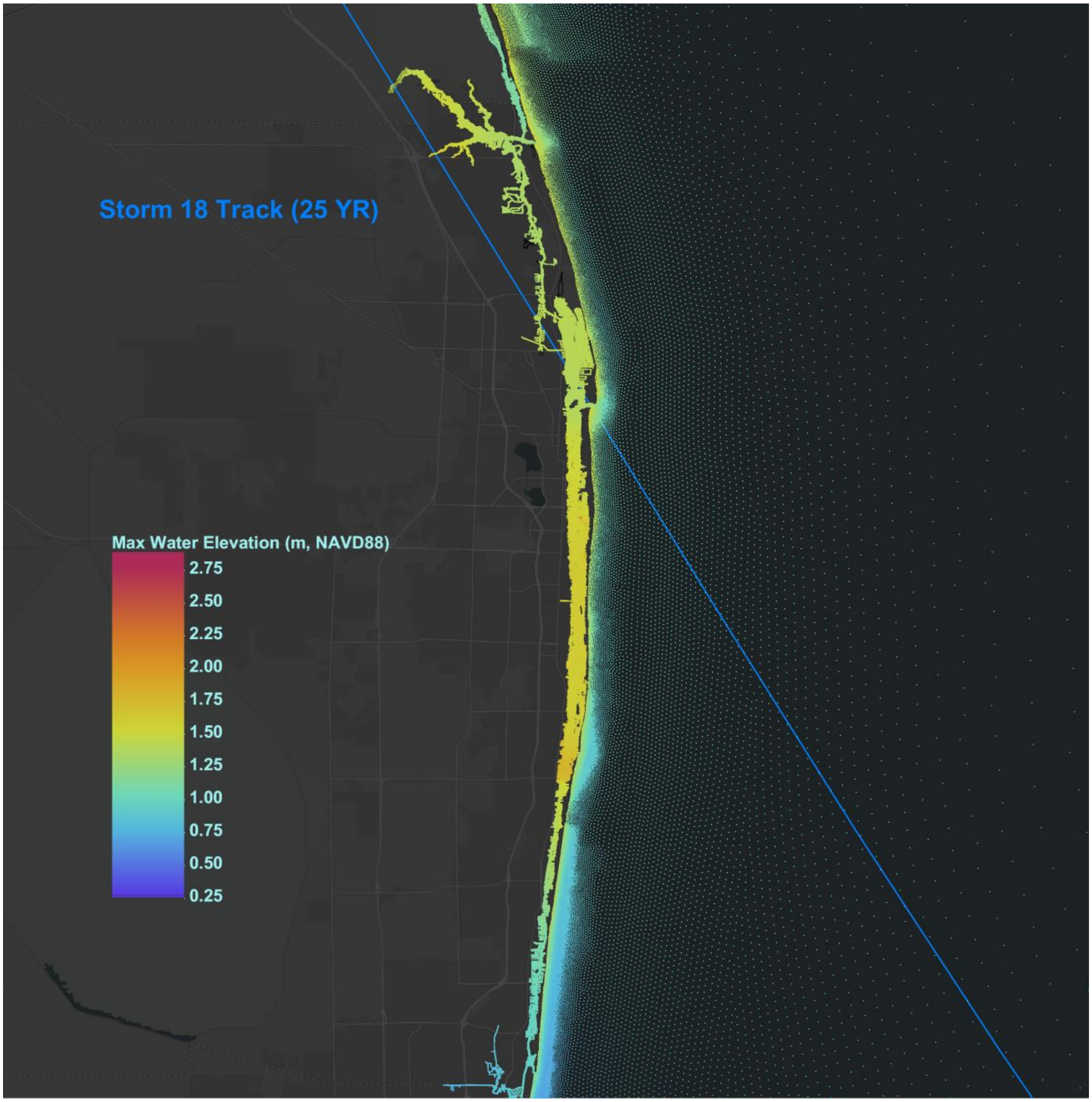

Figure 27. Storm 18 (25 Year Return Period) Original maximum elevation results (County rerun)

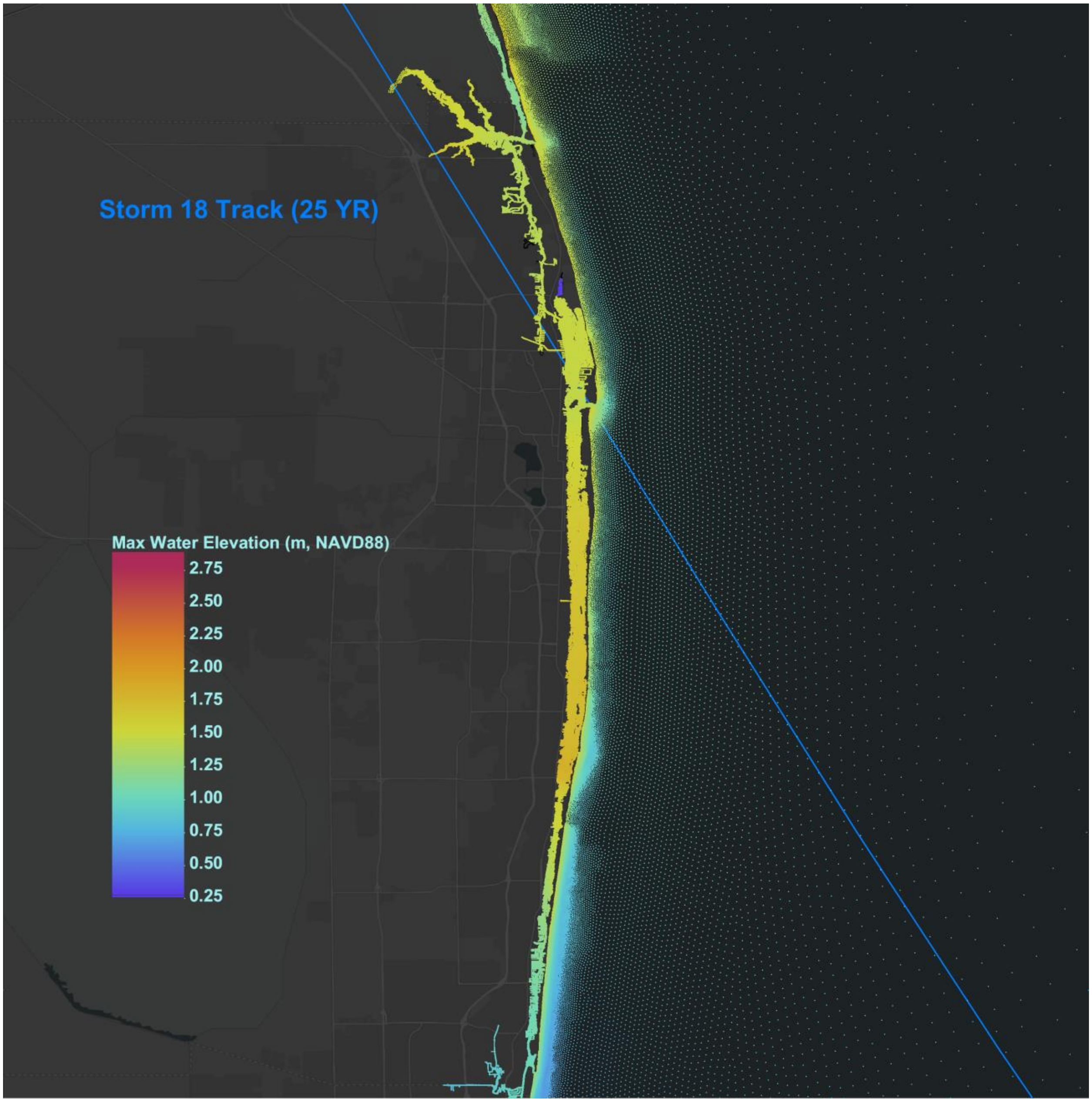

Figure 28. Storm 18 (25 Year Return Period) Original maximum elevation results provided by FEMA

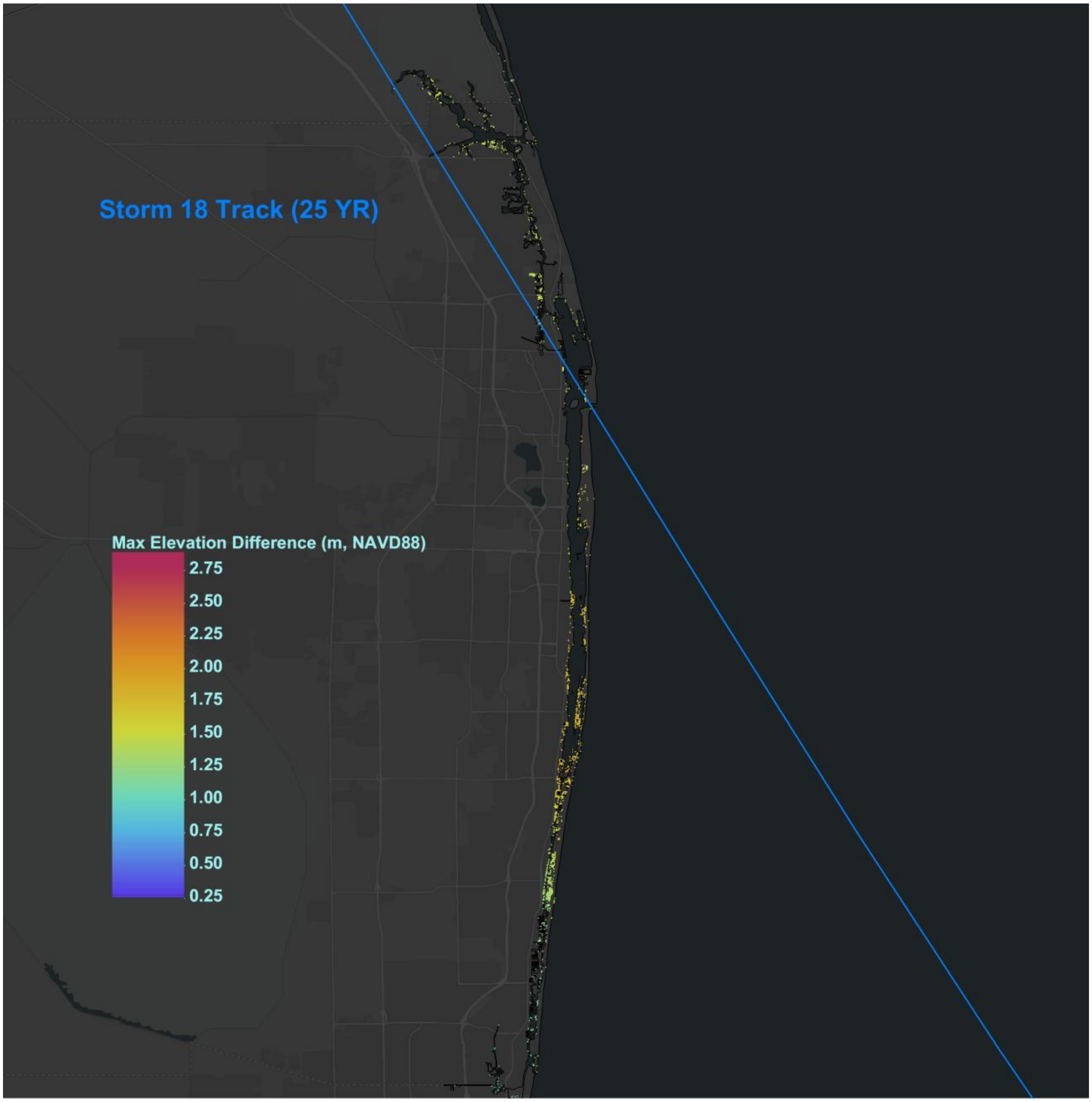

Figure 29. Storm 18 (25 Year Return Period) Original maximum elevation difference (Original minus rerun)

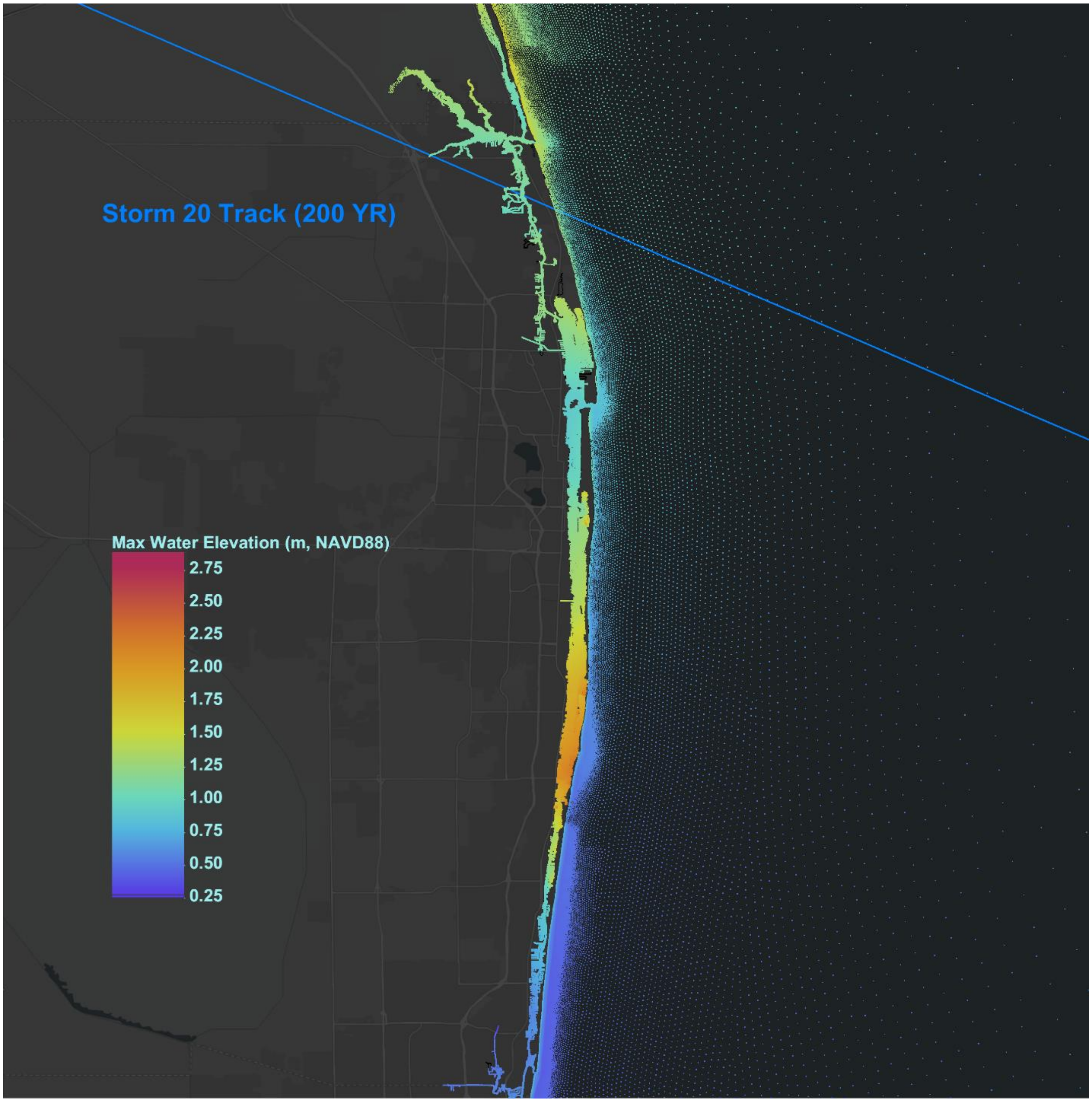

Figure 30. Storm 20 (200 Year Return Period) Original maximum elevation results (County rerun)

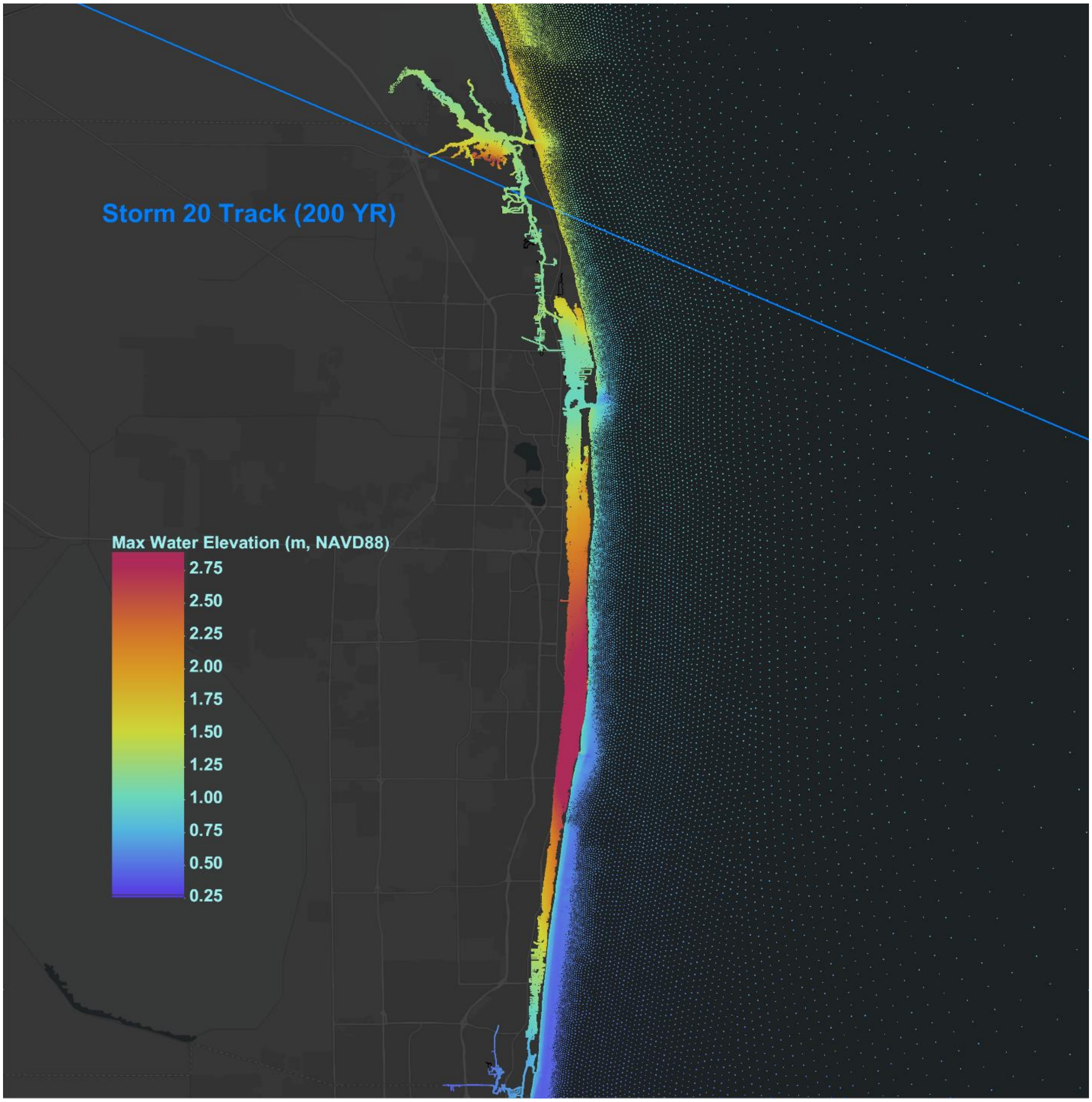

Figure 31. Storm 20 (200 Year Return Period) Original maximum elevation results provided by FEMA

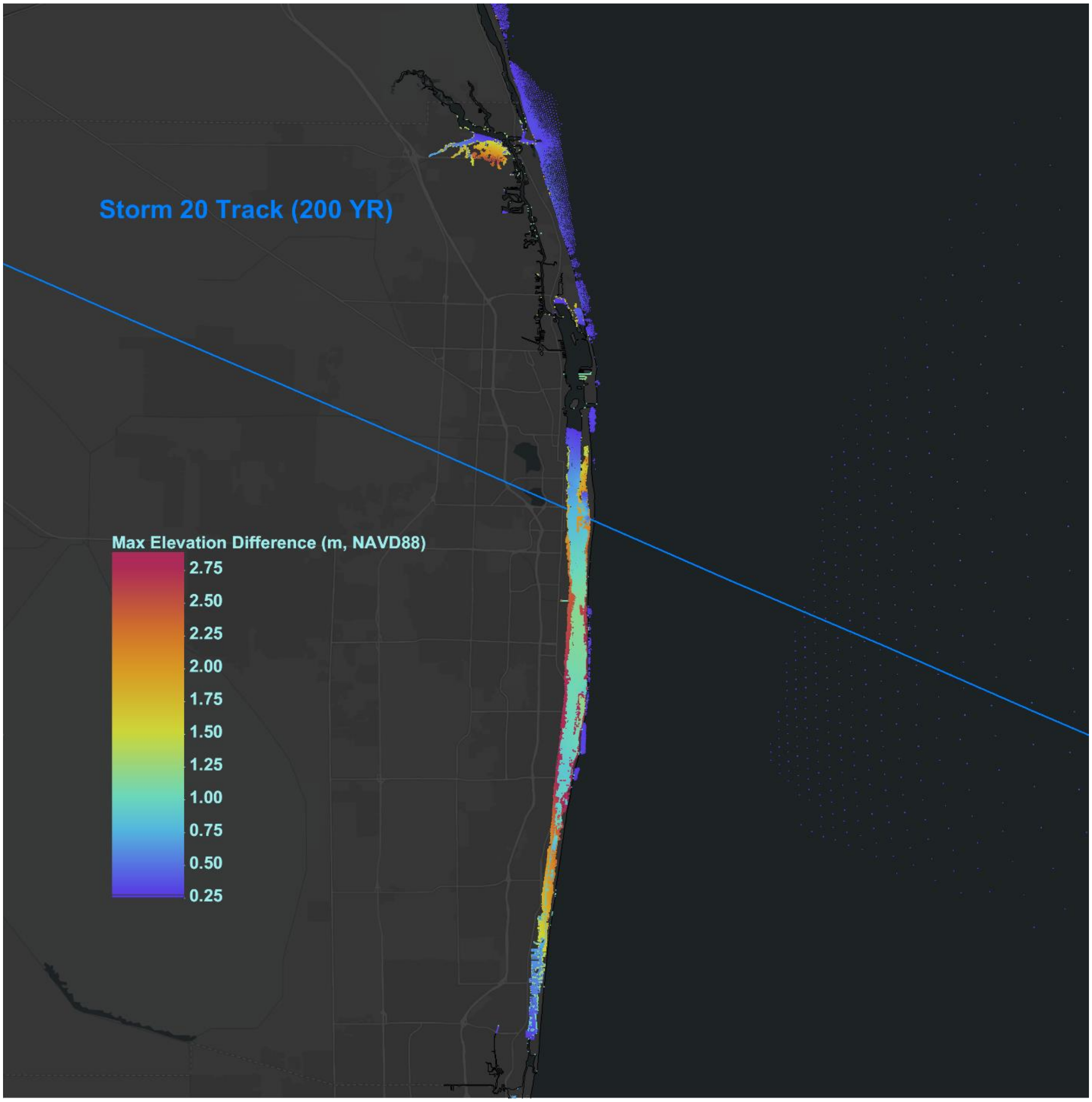

Figure 32. Storm 20 (200 Year Return Period) Original maximum elevation difference (Original minus rerun)

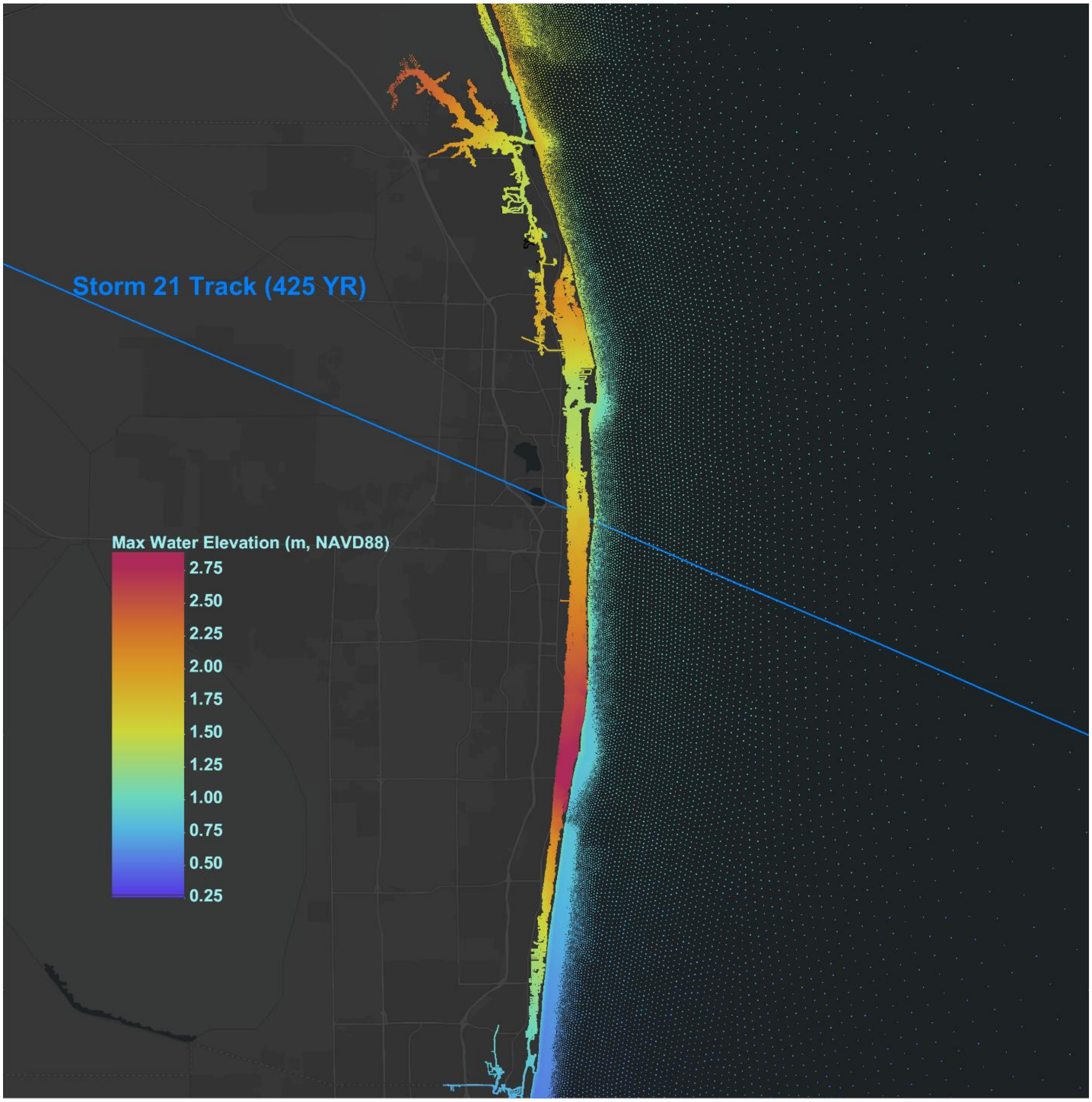

Figure 33. Storm 21 (425 Year Return Period) Original maximum elevation results (County rerun)

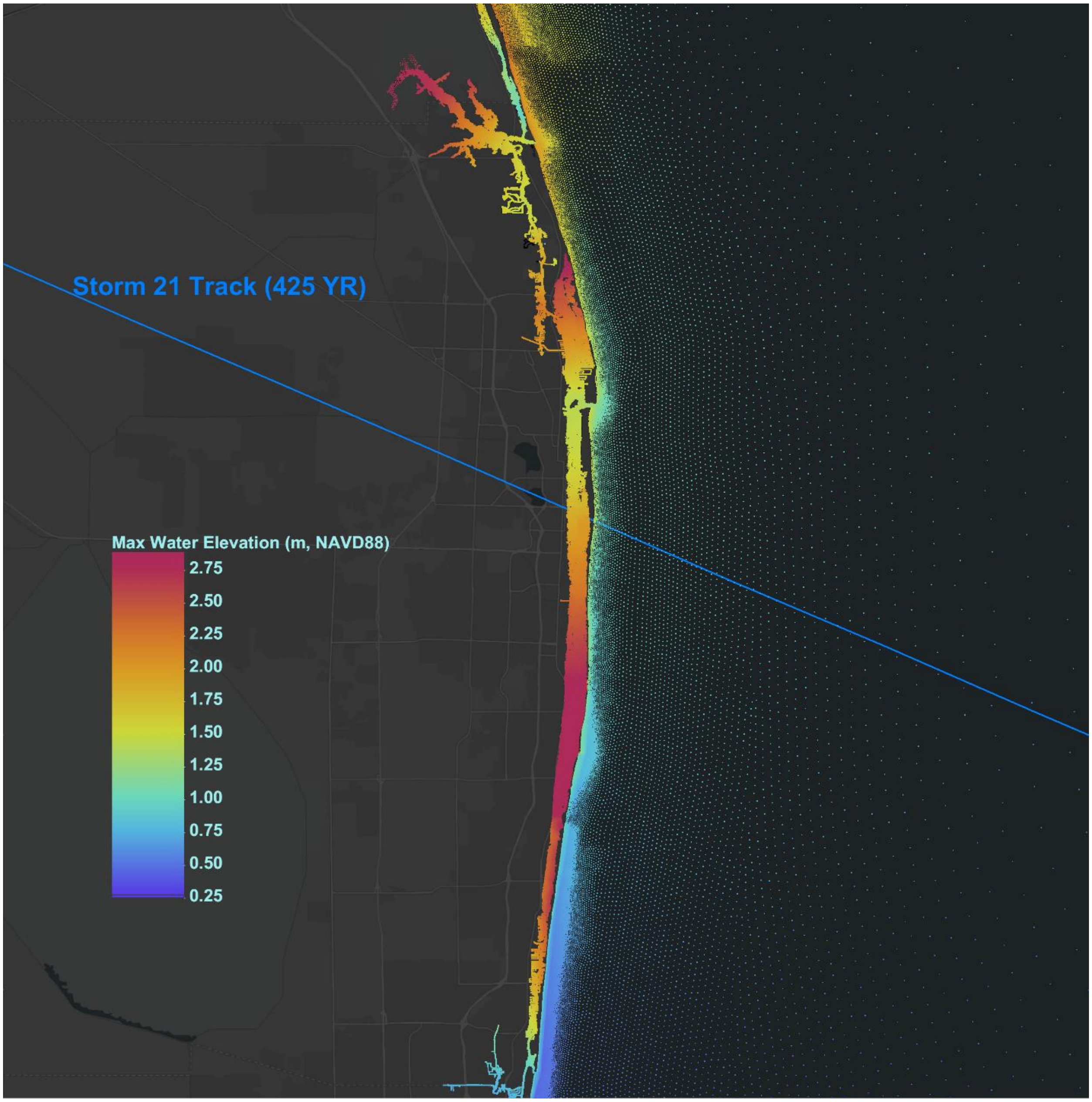

Figure 34. Storm 21 (425 Year Return Period) Original maximum elevation results provided by FEMA

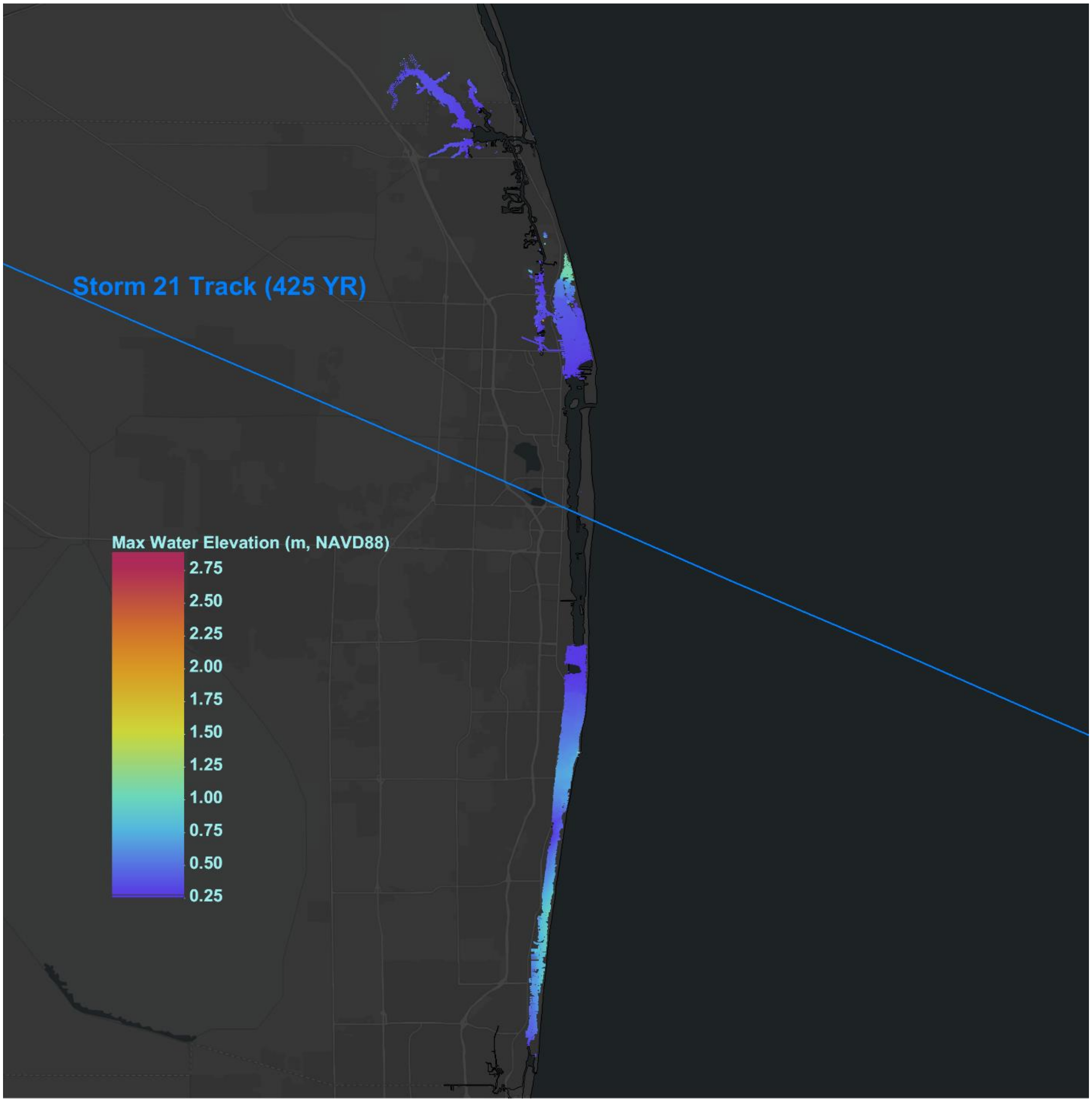

Figure 35. Storm 21 (425 Year Return Period) Original maximum elevation difference (Original minus rerun)

Model run for tide effects

FEMA's reports states: "Each production run began with a model hot-start tide level derived from a three-month tide simulation. The tide simulation covered the period from August 1 to October 31, 2015 to cover the period when most major hurricanes make landfall along Florida's east coast. The three-month simulation followed a 30-day spin-up period to provide sufficient tidal forcing ramping before the first storm occurred."

FEMA report however does not state that the three-month tidal simulation is a combination of short runs between each synthetic storm start time. Each short tidal run is hot-started from the previous tidal run. This is a very uncommon application since it creates an environment very susceptible to error. If an error occurs at any point during the three-month tide simulation, the error is then carried over to all the tidal runs that follows. Common practice is to run a 30-day tidal ramp for each storm separately. FEMA also converted the Monte Carlo distribution of start times for each storm into days (as required by ADCIRC). This conversion creates input values that are irrational numbers (e.g., RNDAY = 79.66666…). This not only makes the application error prone but also known to create problems with ADCIRC, especially if the source code is compiled with GFORTRAN compilers. This could have been easily prevented by rounding the start times to the nearest quarter hour with negligible implications on starting tidal levels

4.3 Model Uncertainty Applied Incorrectly

Description of the Deficiency

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, 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.

Why FEMA's Data, Methods and/or Assumptions are Incorrect

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 36 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 36** 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 36** 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 36**. 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.

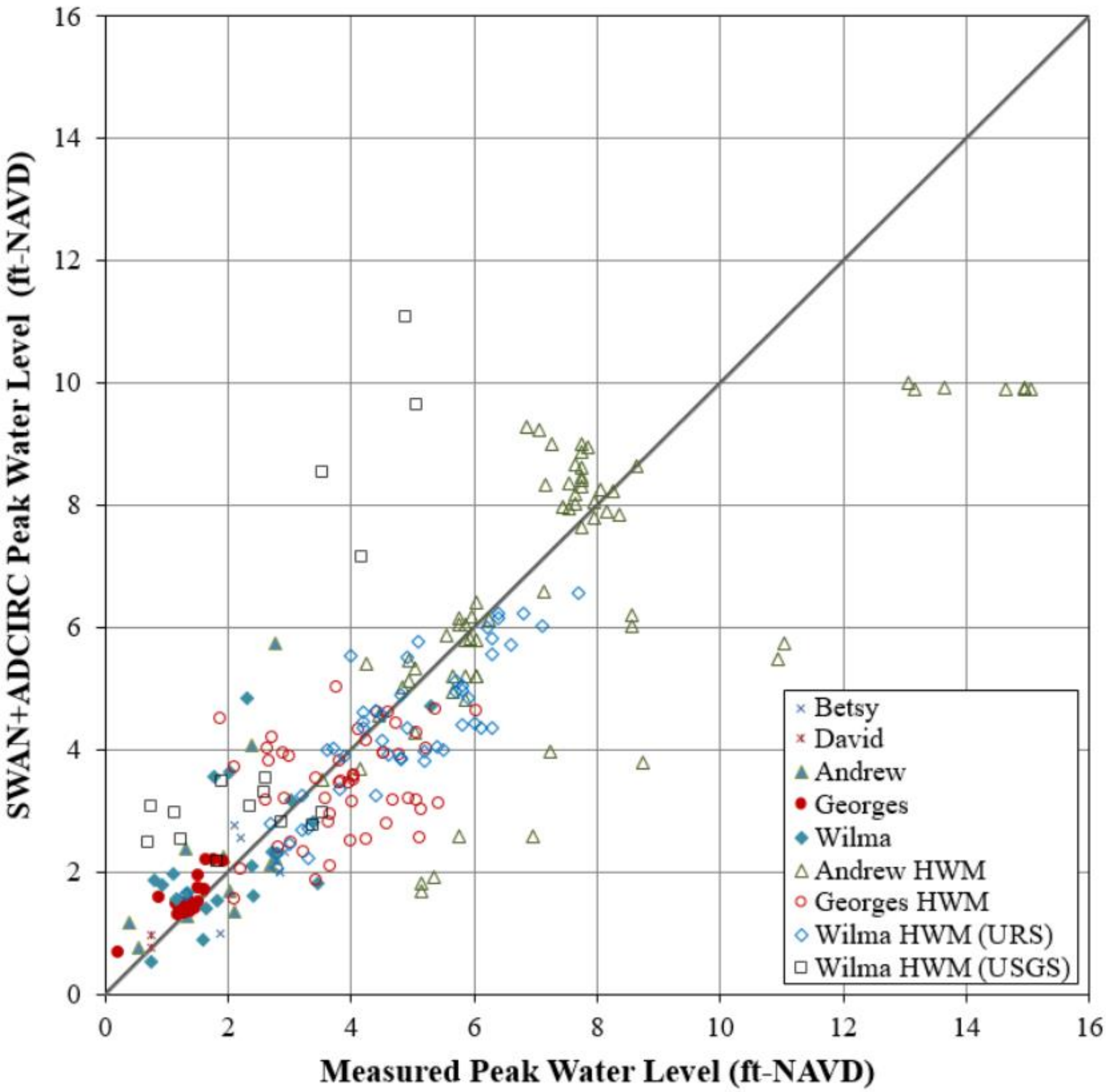

Figure 36. Measured-to-Modeled Peak Water Level Comparison for All Storms (FEMA, 2017)

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 37**, 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.

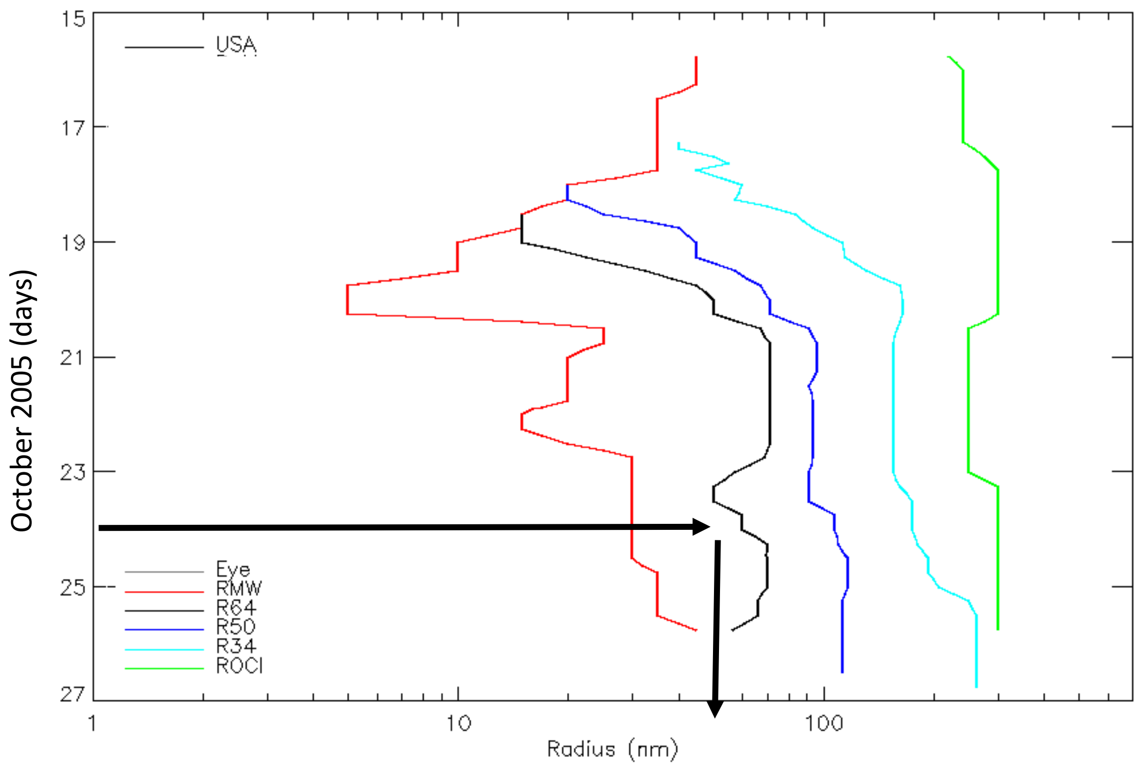

Figure 37. Hurricane Wilma - Wind Field Time Series (NOAA, 2020)

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 38** through **Figure 42**. This analysis is summarized in **Table 4** 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 4. 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.

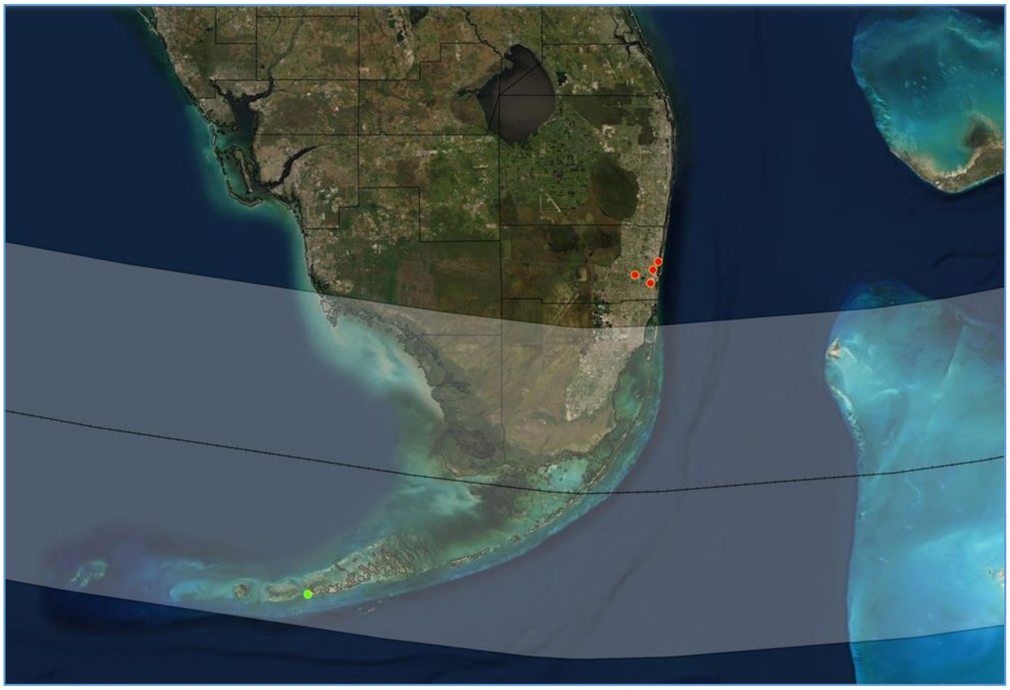

Figure 38. Measured Water Level Locations relative to Storm Track Offset – Hurricane Betsy

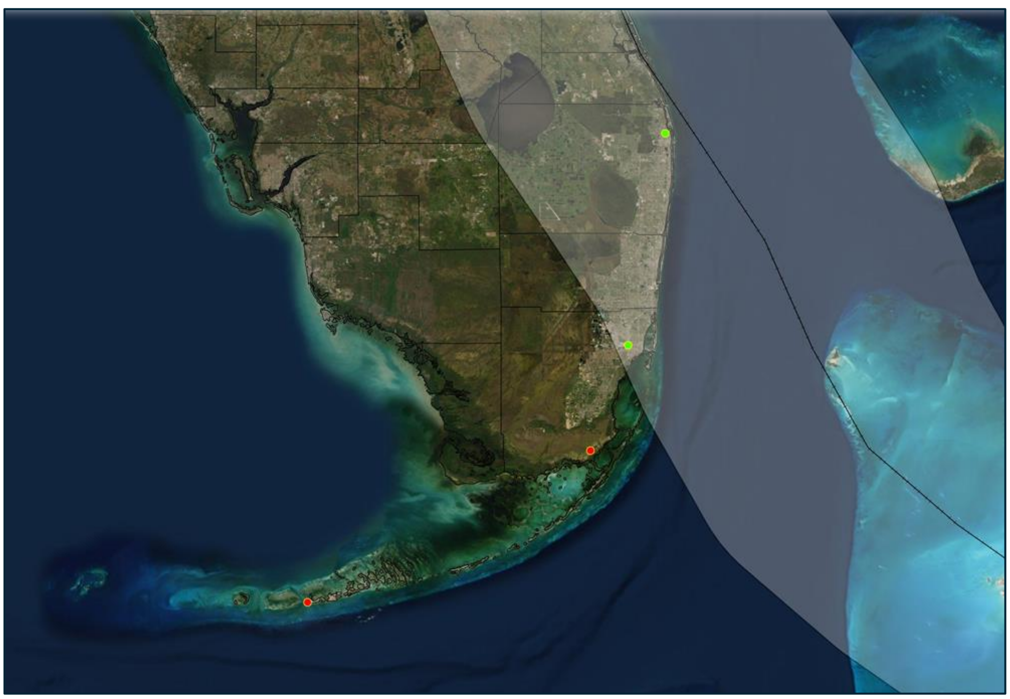

Figure 39. Measured Water Level Locations relative to Storm Track Offset – Hurricane David

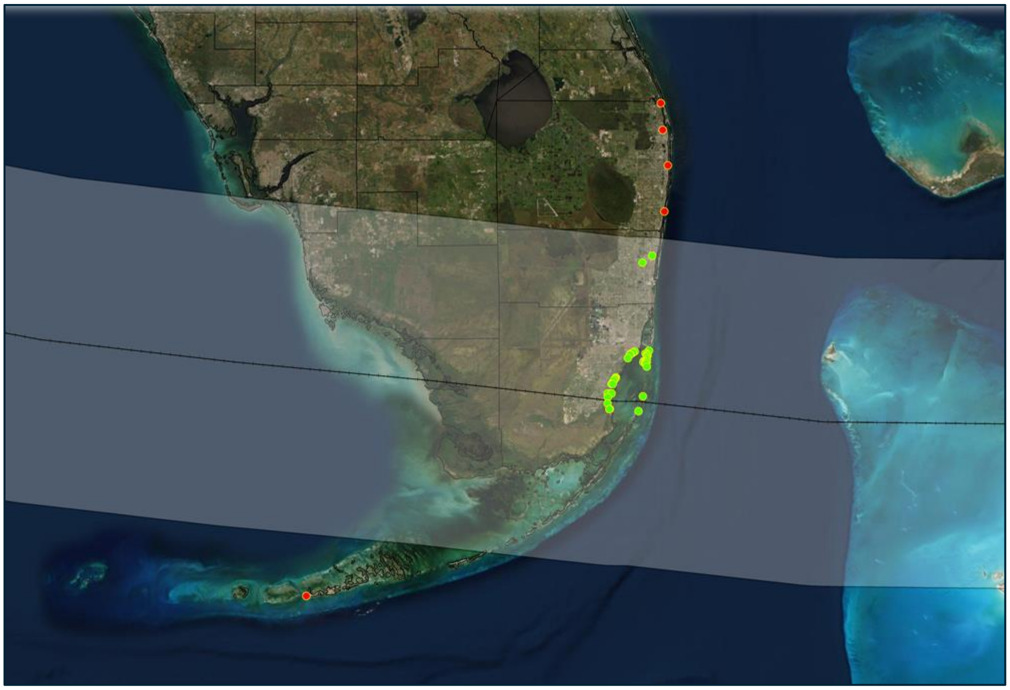

Figure 40. Measured Water Level Locations relative to Storm Track Offset – Hurricane Andrew

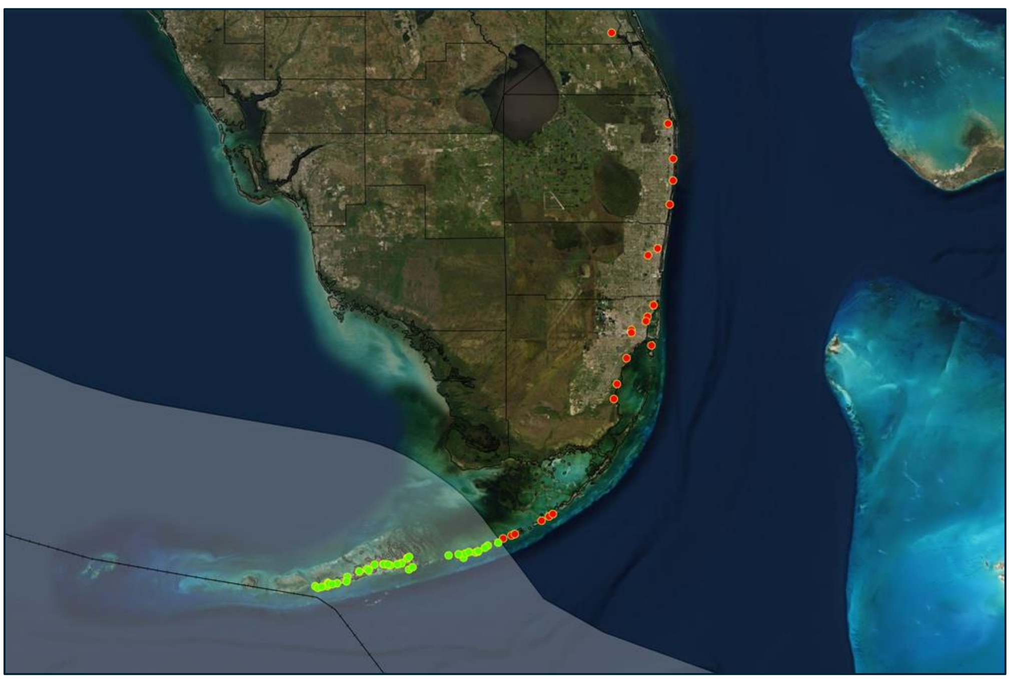

Figure 41. Measured Water Level Locations relative to Storm Track Offset – Hurricane Georges

Figure 42. 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 4**, 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 5. 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

Alternative Analysis Using More Correct Data and Methodologies

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 6**).

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 6. 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 43**. Clustering of points along the diagonal line in **Figure 43** 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 may have contributed to greater model uncertainty and ultimately increased statistical SWEL.

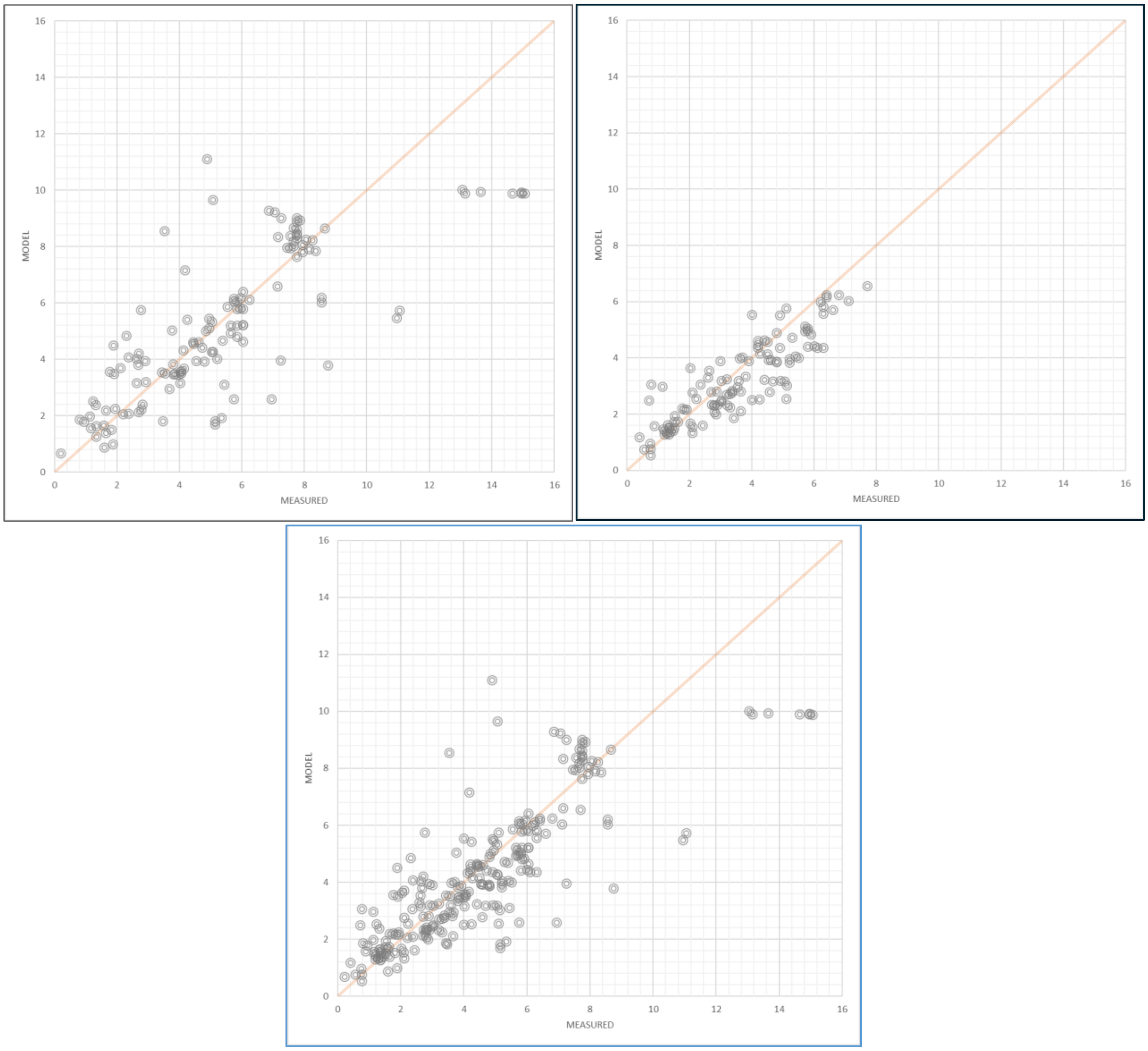

Figure 43. Measured-to-Modeled Peak Water Level (top right panel: Within Offset; top left panel: Outside Offset; bottom panel: FEMA/all)

5.0 Outdated Topographic Elevation Data Used

Palm Beach County collected new LiDAR in 2018 that was not used in the coastal analysis and flood hazard mapping.

The topographic data, used by FEMA for Palm Beach County, in the development of the digital elevation model (DEM) for the Coastal Study was compiled from various datasets. The data collection dates ranged from 2001 to 2007. The resulting DEM had a 10-foot grid and is herein referred to as Southwest Florida Topo-Bathy (SWFLTB) DEM. In 2016, the U.S. Army Corps of Engineers (USACE) produced a 10-foot grid Light Detection and Ranging (LiDAR) model for portions of the barrier islands within Palm Beach County, which was later used in the creation of the USACE DEM, along with the SWFLTB DEM data for the creation of the updated Flood Insurance Rate Maps (FIRMs). During the same timeframe, the U.S. Geological Survey conducted an extensive LiDAR survey for all of Palm Beach County based on a 2-foot grid; herein referred to as PBC DEM.

- Coastal Study – SWFLTB DEM
- Updated FIRMs – USACE DEM
- 2016/2017 Palm Beach County LiDAR for comparison – PBC DEM

There are a total of approximately 92,935 acres contained within the Palm Beach County coastal FIRM panels, not including the surface water area. Within the coastal FIRM panels, areas were examined for elevation differences of 0.5 feet or greater and 1 foot or greater between the PBC DEM and SWFLTB DEM and between the PBC DEM and USACE DEM. Based on the accuracy of FEMA FIRMs and survey tolerances of the data used in this analysis, a deviation of 0.5 feet or greater was deemed to be large enough to possibly affect mappings of flood zone of the updated FIRMs.

- Differences of less than +/-0.5 feet between the DEM's were documented for 73.6% of the coastal FIRM panel area when comparing the PBC DEM to the SWFLTB DEM; 59.0% within incorporated boundaries and 14.6% within unincorporated boundaries. Similar trends were identified when comparing the PBC DEM to the USACE DEM.
- The USACE DEM, which incorporated more recent survey data, exhibited better agreement with PBC DEM.

Elevation differences outside of FEMA's special flood hazard areas (SFHA) have limited, if any, influence on the updated FIRM maps. Elevation differences between the PBC DEM and the SWFLTB DEM as well as the PBC DEM and the USACE DEM were compared within the footprints of the FEMA's mapped Changes Since Last FIRM (CSLF). The footprints of the CSLF were estimated at 11,509 acres as compared to 92,934 acres within the coastal FIRM panels. Within the CSLF footprints (**Table 7**), the following was determined:

- Incorporated boundaries represented 83.9% (9,659 acres) of the area included in the CSLF footprints; unincorporated boundaries represented 16.1% (1,850 acres) of the area.

- Differences of less than +/-0.5 feet between the DEM's were documented for 78% of the CSLF footprints when comparing the PBC DEM to the SWFLTB DEM; 65.0% within incorporated boundaries and 12.9% within unincorporated boundaries. Similar trends but with increased agreement for differences less than +/-0.5 feet (as noted above) were identified when comparing the PBC DEM to the USACE DEM.
- Difference of greater than 0.5 feet between DEM's were documented for 22.0% of the CSLF footprints when comparing the PBC DEM to the SWFLTB DEM; with the PBC DEM being above the SWFLTB DEM for 15.0% (1,732 acres) of the area and below for 7.0% (804 acres) of the area.

Table 7. PBC DEM minus SWFLTB DEM within CSLF Footprints

PBC DEM minus SWFLTB DEM	Incorporated (acre)	Unicorporated (acre)	Total (acre)	Incorporated (%)	Unincorporated (%)	Total (%)
PBC ≥ 1.0 foot above	509	112	621	4.4%	1.0%	5.4%
PBC 0.5 to 1.0 feet above	964	147	1,111	8.4%	1.3%	9.7%
PBC < 0.5 feet above/below	7,486	1,487	8,973	65.0%	12.9%	78.0%
PBC 0.5 to 1.0 feet below	473	66	539	4.1%	0.6%	4.7%
PBC ≥ 1.0 feet below	227	38	265	2.0%	0.3%	2.3%
Total	9,659	1,850	11,509	83.9%	16.1%	100.0%
PBC above	1,473	259	1,732	12.8%	2.3%	15.0%
PBC below	700	104	804	6.1%	0.9%	7.0%

Based on the DEM comparisons, inclusion of the PBC DEM in FEMA's coastal study would help address the following:

- Differences may have expanded (overestimated) the inland extents of the SFHA mapped by FEMA in the central portion of the County. The DEM comparisons indicated that the PBC DEM was approximately 0.5 to 1.0 feet above the SWFLTB DEM west of the Lake Worth Lagoon. The differences (FIRM panels 0393, 0581, 05983, 0591, 0593, 0781, 0783, 0791, and 0793) extended approximately 15.5 miles between 45th Street, West Palm Beach and East Ocean Avenue, Boynton Beach. The differences appear to be inherent to the 2007 Florida Department of Emergency Management LiDAR data used by FEMA to generate the DEM in this area and therefore may be attributed to data collection techniques (e.g. flight lines, airframes, sensors, equipment).
- Differences may have limited (reduced) the inland extents of the SFHA mapped by FEMA in the southern portion of the County. The data used by FEMA in the creation of the SWFLTB DEM changed from the 2007 Florida Department of Emergency Management to the 2001 Palm Beach County LiDAR and resulted in an apparent vertical offset. The differences (FIRM panels 1159, 1178, and 1179) indicated that the PBC DEM was approximately 0.5 to 1 foot below the SWFLTB DEM.
- Larger differences (e.g. greater than 1 foot) appear to be due in part to the occurrence of construction and development during the time between the capture of the SWFLTB DEM in 2007 and the PBC DEM in 2016/17. Differences identified by the DEM comparisons may also be attributed in part to post-processing of the survey data and gridding methods. LiDAR survey data is processed to eliminate buildings, trees, and other obstructions to represent "bare earth" (i.e. ground elevations). Post-processing techniques, gridding methods, and

technological advances in data collection since 2007 may account for some of the differences identified herein. A location-by-location analysis (which was beyond the scope of work) is necessary to evaluate whether these differences with respect to updated base flood elevations (BFEs) would affect/alter the mapping of flood zones shown in FEMA's preliminary FIRM panels.

6.0 Additional Items that Impact Base Flood Elevations

6.1 Treatment of Tidal Data

Tidal optimization was completed by randomly assigning a start date to each event within a representative 3-month period (August-October 2015). A predicted tidal boundary condition, based on this start date, is applied to the ADCIRC model. This means that some events, considered to impact the 2-, 1- and 0.2% annual chance surge elevations, will occur at low tide and likely not impact on the extreme SWELs. The report goes on to state that one replication of the assignment of tidal conditions is sufficient. This is based on the other studies and it is not clear that the overall approach does not under sample the extreme SWELs.

It is not demonstrated that the selected 3-month tidal period (August-October 2015) is representative of the long-term data period. Tidal range histograms indicate that the 3-month period over represents the larger tidal ranges. It is unclear if these histograms are predicted tidal data or measured water level data. If predicted data, the selected period will over sample higher tide levels and potentially impact on the extreme SWEL results. If measured data, the histogram comparisons are not valid for what is being demonstrated (i.e., should use predicted tides as applied to the boundary of the ADCIRC model).

6.2 Validation Storms

Validation of the Simulating WAves Nearshore + ADvanced CIRCulation (SWAN+ADCIRC) model was based on five historical hurricanes: Betsy (1965), David (1979), Andrew (1992), Georges (1998), and Wilma (2005). Inclusion of these storms within the model validation was not appropriate given the magnitude of storm surge generated, the regional extents of the surge, the locations of gage measurements, and limited measured data. Only one of these storms actually made landfall in the County (hurricane Wilma) and that was an exiting storm. Hurricane David skirted the coat of Palm Beach County but only a single data point is available for calibration of the model.

Inclusion of other validation storms in addition to (or in substitution of) those selected by FEMA should be considered. For example, Hurricanes Frances and Jeanne (2004) are potential storms that should be considered for the following reasons.

- The storms provide a basis for representing storm surges along the Atlantic coastline of the study area, specifically within Palm Beach County.

- The storms were used to validate the SWAN+ADCIRC model for FEMA's East Coast Central Florida (ECCFL) coastal study. Inclusion of these storms within the SFL Study may help improve agreement at the study area boundaries (Martin and Palm Beach county line).

7.0 Summary

Palm Beach County has identified technical and scientific deficiencies in the modeling that was performed by FEMA and forms the basis of the Preliminary FIS and FIRMs. The coarse wind and pressure grid that was used for most of Palm Beach County produces unreliable results. Due to the short timeframe of the appeal period, the County was not able to obtain wind and pressure data at a finer resolution and reanalyze all events. However, three selected storms were re-run using only the basin (coarse) scale wind and atmospheric pressure data to show the impacts of the finer regional grid. These runs produced water surface elevations differences of up to 8-feet and will impact the computed Stillwater Elevations and thus the Base Flood Elevations.

Additional problems with the identification and treatment of model instabilities, lack of QA/QC at local level, inconsistent model setup, mesh resolution, assignment of nodal attributes, differences between model re-runs and FEMA's results, the treatment of the model run for tide effects, model uncertainty and validation storms were identified. Also, the County has updated topographic data that was not used in the modeling or mapping.

The County requests that FEMA address the issues identified in the model and reissue FIRMs that reflect the updated model.

8.0 References

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9.0 Appendices

Appendix A – Mesh and Nodal Attributes Applied in Final Storm Run
Appendix B – Topographic Elevation Data Technical Memorandum
Appendix C – Data and Documents Review Technical Memorandum
Appendix D – Storm Surge, Wave Model & Flood Map Evaluation
Appendix E – Relevant Correspondence from Palm Beach County to FEMA