

National Flood Insurance Program Coastal Flood Hazard Analysis

Description of differences between existing effective and preliminary coastal analysis and mapping

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Acronyms and Definitions

ADCIRC – Advanced CIRculation, 2-D Storm Surge Model BFE – Base Flood Elevation CFR 44 – Code of Federal Regulations EST – Empirical Simulation Technique FEMA – Federal Emergency Management Agency FIRM – Flood Insurance Rate Map HBL – Hurricane Boundary Layer, Wind and Pressure Field model IOKA – Interactive Kinematic Objective Analysis JPM – Joint Probability Method NCFMP – North Carolina Floodplain Mapping Program NM – Nautical Mile PBL – Planetary Boundary Layer, Wind and Pressure Field model PFD – Primary Frontal Dune SWAN – Simulating Waves in the Nearshore, 2-D Wave Model WHAFIS – Wave Height Analysis for Flood Insurance Studies

Table of Contents

1.0	Introduction1		
	1.1.	Summary of Effective Coastal Study	.1
	1.2.	Summary of New Coastal Study	.1
2.0 Surge Modeling		odeling	.2
	2.1.	Water Level Stations versus Modeling	.2
	2.2.	Storms	3
	2.3.	Statistical Approaches	.4
3.0	New Stu	New Study Comparison to Effective Study	
	3.1.	Topographic and Bathymetric Information	.6
	3.2.	Land Use	.6
	3.3.	Model Mesh	.7
	3.4.	Climatology	11
4.0	Surge Results1		13
5.0	Transect Analysis Comparison		16
6.0	Combined Probability of Coastal and Riverine Flooding 20		

List of Figures

Figure 1. ADCIRC Model Mesh	2
Figure 2. NOAA Water Level Station in North Carolina	3
Figure 3. Tropical Storms Selected for Analysis	4
Figure 4. JPM Tropical Storm Tracks	5
Figure 5. Combined Tropical (JPM) and Extra-Tropical (EST) Return Periods	5
Figure 6. 5-foot Topographic Map Used in Effective	6
Figure 7. LIDAR Data Used in New Study	6
Figure 8. Effective Surge Model Grids	7
Figure 9. 2 NM Effective Model Grid	8
Figure 10. 1 NM Effective Model Grid	8
Figure 11. ADCIRC Model Grid for North Carolina	9
Figure 12. Detailed ADCIRC Grid of Northern North Carolina	9
Figure 13. Detailed ADCIRC Grid of Central North Carolina	. 10
Figure 14. Detailed ADCIRC Grid of Southern North Carolina	. 10
Figure 15. Storms that Impacted North Carolina Since 1980	. 11
Figure 16. Major Tropical Storms that Impacted North Carolina since 1980	. 12
Figure 17. Differences between Effective and Updated 1% Storm Surge Elevations	. 13
Figure 18. 1% Storm Surge Elevations near Beaufort Inlet	. 15
Figure 19. ADCIRC Model Grid in New River	. 16
Figure 20. ADCIRC Grid vs. Effective Model Grid near City of Jacksonville	. 16
Figure 21. New Study Coastal Transects	. 17
Figure 22. Southern Carteret County Transects	. 18
Figure 23. Northern Carteret County Transects	. 19
Figure 24. Reverse Transects	. 19
Figure 25. Wave Runup Analysis and Mapping	. 20
Figure 26. Coastal/Riverine Combined Probability Example	. 21
Figure 27. Effective North Carolina Counties with Coastal/Riverine Combined Probability Analysis	. 21
Figure 28. Shallotte Creek Coastal/Riverine Combined Probability Results	. 22

1.0 Introduction

A new coastal flood study has been prepared for the State of North Carolina. The coastal flood study is being used to update the Flood Insurance Rate Maps (FIRMs) for each coastal county in the state. The new coastal study updates the 1-percent-annual-chance storm surge values as well as the expected 1-percent-annual-chance storm induced erosion analysis, overland wave propagation, and wave runup analyses. These updated analyses are used to map new coastal floodplains and Base Flood Elevations (BFEs). The differences between the new coastal analysis when compared to the effective data can be significant in extent and impact, resulting in both increases and decreases in elevation and extent, depending on location. This document describes the differences between the effective and new coastal analysis so that it can be understood why these changes in mapped flood risk are occurring.

1.1. Summary of Effective Coastal Study

Even though there were several community level updates to the coastal analysis and mapping over time, the current base storm surge elevations still in effect were derived from the storm surge modeling study that was completed by Tetra Tech in 1981. The effective surge study used a method of coarse grids, and more detailed sub-grids while the updated analysis adds greater accuracy in the nearshore, bays, and estuaries. The most recent effective updates vary significantly by county. A majority of the counties effective coastal flood studies are still based on old topographic information that dates back to the 1970s. For Carteret, Onslow and Pender (North of Topsail Inlet) Counties only a re-delineation of the existing BFEs and mapping to newer topographic information was made with the previous revisions for the current effective map revisions performed in the 2000s. Other counties such as Dare County used the 1981 surge study as a base to update the overland wave modeling, and the mapping used the latest topographic information. The storm surge study from the effective studies was performed on a model grid using a 2D model called TTSURGE. The coastal overland modeling was performed using a transect based analysis using the Wave Height Analysis for Flood Insurance Studies (WHAFIS) Model. Storm-induced erosion analysis was also performed on the dunes along the barrier islands in the effective studies. The Code of Federal Regulations (CFR 44) rule on extending the VE Zone to the landward limit of the Primary Frontal Dune (PFD) was also applied in the effective studies. Wave setup, the additional water level due to wave breaking, was applied to all counties with coastal flooding during the effective flood study updates, with the exception of Onslow and Carteret County and Topsail Beach and Surf City in Pender County, where wave setup was only applied along the open coast, but not to the inshore sounds/bays/estuaries. The effective wave setup methodology utilized simple empirical equations to estimate wave setup. Wave runup calculations were not applied to any effective study.

1.2. Summary of New Coastal Study

The new storm surge study covers the entire state of North Carolina. There is one model grid that covers the entire state. The model grid starts off coarse offshore and gets considerably tighter as it approaches the coastline and moves inland (Figure 1). The new storm surge analysis incorporates 25+ years of new storm data, over which time North Carolina coastal areas experienced many new large storm events. The storm surge modeling system used a 2-D model called ADvanced CIRCulation (ADCIRC) model to simulate storm surge levels. The study also utilized a 2-D wave model called Simulating Waves in the Nearshore (SWAN) model. The SWAN model integrates the calculation of wave setup into the hydrodynamics of the ADCIRC

simulations so that the results are inclusive of wave setup. The results of the SWAN model are also used in the new study to provide starting wave conditions for the transect analysis. The new coastal analysis also uses the WHAFIS model for overland wave modeling. Additionally, wave runup modeling is now being included where the storm surge is interacting with high dunes or steep bluffs near the shoreline. Finally, the VE Zone is being mapped to the landward limit of the PFD and adjustments are being made to its location from the effective study locations based on more accurate and updated topographic information.



Figure 1. ADCIRC Model Mesh

2.0 Surge Modeling

2.1. Water Level Stations versus Modeling

Many people wonder why water level stations or gages are not used to determine flood level elevation since the gages are directly recording the water levels experienced during storms. The main reason gages are not used is because of the sparse density of gages along the coastlines. For instance, NOAA has only 7 active water level stations for the entire state of North Carolina (Figure 2). Most of these 7 stations are at or near the open coast of the Atlantic Ocean, and there is virtually no coverage in the bays and estuaries. In order to capture the surge impacts throughout the state a 2D surge model must be used.

Another reason gages are not used is that a gage may not capture all the storm level impacts that can potentially occur in the area. For example, a large storm could have tracked just north of a gage where the water level elevation recorded at the gage could be minimal or even show water levels below normal due to the counterclockwise rotation of tropical storms. The fact that the storm track is a random variable, meaning that a particular storm could have just as easily taken a different track, means that the area of the gage has the same uniform potential risk to that storm as other areas. The gage analysis could not have accurately predicted that risk because the stormed happened to spare the gage area from maximum surge impacts. There are other factors as well, such as some existing gages have not been in operation long enough to provide a sufficient period of record for a valid analysis, which is usually more than 25 years. Additionally, during the largest water level storms gages often break and fail to capture the peak water levels.

In summary, we use modeling to obtain accurate results in areas not captured by gages and to ensure the appropriate risk for all potential storms is considered.



Figure 2. NOAA Water Level Station in North Carolina

2.2. Storms

Both Tropical storms and extra-tropical storms, known as Nor'easters, are important to determining flood hazards in North Carolina. In the effective study as well in the new coastal study Extra-tropical storms were considered, however North Carolina sits at the dividing line where extra-tropical storms begin to have a greater impact to a statistical coastal flooding approach. That dividing line sits at around Cape Hatteras, and in the effective study extra-tropical storms were factored into the analysis only for the areas of North Carolina north of Cape Hatteras, mainly Dare and Currituck Counties. For the new coastal surge study extra-tropical storms were considered state-wide. Even though the greatest impacts can be north of Cape Hatteras it was found that extra-tropical storms can contribute to the overall statistical analysis throughout the state.

Historic storm data is collected going back to approximately 1940. The storms that had the greatest impacts to the North Carolina coastlines were selected for analysis, as represented in Figure 3. A few of these storms with the greatest surge impacts and that are well documented were selected to help validate that the surge and wave models are performing well. Due to the large geographic extent of North Carolina, 4 tropical (Emily (1993), Fran (1996), Isabel (2003), and Ophelia (2005)) and 2 extra-tropical storms (2006 Thanksgiving Storm and 2006 extra-tropical Ernesto) were selected for validation of the models. The results of these storms is compared to water level recordings at NOAA stations, as well as collected high water marks for those historic storm. The effective surge modeling study was validated using two storms, Hurricane Hazel in 1954 and Hurricane Donna in 1960.

Figure 3. Tropical Storms Selected for Analysis



2.3. Statistical Approaches

There are two different statistical approaches used in North Carolina. What's known as the Empirical Simulation Technique (EST) is used to determine the flood elevation return periods of extra-tropical storms, and the Joint Probability Method (JPM) is used for tropical storms. The reason for this is that extra-tropical storms are difficult to define in terms of unique characteristics, as opposed to tropical storms which can be broken down into unique parameters that define the storm, such as central pressure, radius to maximum winds, and forward velocity. Each of these parameters for a tropical storm can vary in different combinations to make up the storm, hence each historic storm has unique impacts and all of the different combinations of these parameters must be accounted for. Each parameter is analyzed separately for its probability of occurring in the North Carolina study area, and then combined together into a joint probability for each particular storm simulated, hence the JPM method. Each of these combined parameter storms (known as synthetic storms, because they did not actually occur but have a unique probability of occurring based on the parameter makeup of the historic storms that impacted North Carolina) are then simulated in the storm surge 2-D Model ADCRIC as well as in the 2-D wave model SWAN.

Each of the synthetic storms are simulated on a network of storm tracks (see Figure 4) that are based on the typical storm tracks that historically have affected North Carolina. Because storm track and landfalling location are random variables, storm tracks are spaced up and down the coast of North Carolina. Each one of the tracks also comes with a probability of occurrence based on the historic tracks. These tracks are combined with the synthetic storms to make a total of 675 individual storm simulations for North Carolina.



Figure 4. JPM Tropical Storm Tracks

Since they cannot be broken down into separate parameters, Extra-tropical storms were simulated in the models exactly how they occurred historically. In North Carolina 22 historic extra-tropical storms were simulated. The surge results were then used with the EST approach to determine the water elevation return periods of the Extra-tropical storms.

The tropical and extra-tropical return periods were then merged into a combined probability result. Each of the frequencies of the same water level from the tropical and extra-tropical analysis are added to give a combined frequency of that water level, the combined data is plotted, and a final 1-percent-annual-chance storm surge level is determined. Figure 5 shows the extra-tropical EST return periods, the tropical JPM return periods, and the combined.



Figure 5. Combined Tropical (JPM) and Extra-Tropical (EST) Return Periods

3.0 New Study Comparison to Effective Study

There are several data sets used to create inputs to the coastal models that have improved significantly since the effective studies. These input data sets can have large impacts on the results of both the surge modeling and the overland wave transect analysis.

3.1. Topographic and Bathymetric Information

Topographic and bathymetric information forms the base of any model and is the most important input data set. In the 2-D models it is a direct representation of the geography and hydraulic flow paths. In the 1-D transact models it represent the ground elevation profile used to define the depth.

In the effective storm surge study the ground elevations were based on USGS topographic paper maps with contour intervals of up to 5 feet (see Figure 6). In the new coastal study digital LiDAR is used and greatly increases the accuracy of the ground elevations (see Figure 7). Base bathymetric data for both the effective and new studies was obtained from NOAA NOS hydrographic surveys ranging in dates from the 1800's to 2010. However for the new study updated bathymetry was used where available. This updated bathymetry for the new coastal analysis included bathymetric LiDAR to better define the nearshores areas of the open coast, USACE Inlet and channel surveys to better captures the hydrodynamics of surge propagation between the open ocean, bays and rivers, and beach profile ground surveys for more accurate beach and dune elevations.



3.2. Land Use

Land use information such as developed areas, vegetation, and marsh is used to represent roughness for the various models used in the study. The roughness provides friction and influences the wind speeds, surge propagation, and wave heights throughout the study area. In the effective surge study the roughness was

only applied as a ground friction and only two values were used, one for overland areas, and one for ocean or water areas. In the effective study some sub-grid features were also assigned specific elevation values, such as barrier islands and dune heights, as well as inlets. These sub-grid features could not be captured by the resolution of the surge model grid. These values were also applied to the surge grid of 1 Nautical Mile (NM). In the new surge study the ground roughness is applied in a more detailed analysis by adopting the exact land use type of each of the detailed grid elements. It is also applied in the surge study as a directional wind reduction factor, meaning depending which way the wind is blowing for a particular storm a different reduction to the wind speed is applied over each grid element. In the effective studies and the new coastal studies where wave analysis was performed, the land use data is used to obtain obstruction information. Obstructions such as buildings, trees, and marsh grass are input to the WHAFIS modeling to dissipate and reduce wave heights.

3.3. Model Mesh

The model grid is a representation of the geography and the topographic and bathymetric elevations. Each grid is a representation of the elevations over which the grid size covers, hence the smaller the grid size the more detailed the model is and the more small scale features that can be represented in the model. The effective study modeling grid from the 1981 study (Figure 8) had two 5 NM rectangular grids covering the state. The models only had one 2 NM rectangular grid capturing the northern sounds and barrier islands (Figure 9). A 1 NM rectangular grid was only used from the confluence of the rivers within the northern bays. The 5 NM rectangular grid results provided boundary conditions for the 2 NM rectangular grid, and the 2 NM rectangular grid provided the starting conditions for the 1NM grid at the rivers. A 1 NM grid was also used for the barrier islands, bays, and estuaries south of Cape Lookout. The 1 NM rectangular grids south of Cape Lookout used results from the 5 NM rectangular grid as a boundary condition. Figure 10 is an example of the 1 NM grid used for the New Hanover County area.



Figure 8. Effective Surge Model Grids

Figure 9. 2 NM Effective Model Grid



Figure 10. 1 NM Effective Model Grid



In the new surge study there is one grid that covers the entire Atlantic and Gulf basins (Figure 11). Each storm is simulated over this grid so that the hydrodynamics of the entire Atlantic basin are captured as the

storms move from the open ocean to the coastline of North Carolina. It is a variable triangular grid going from a coarse grid offshore which transitions to a finer, more detailed grid over the barrier islands, bays, and inland in the state of North Carolina. The grid goes down to approximately 300 feet on a side at the coastline and inland. Some areas in the grid get down to a 45 foot grid to capture the greatest details. Each grid node is representative of the ground elevation at the node location. The new North Carolina grid terminates at a vertical elevation inland of approximately 45 feet, while the effective surge study vertical extents varied by grid coverage and often end within water bodies. Figures 12 - 14 show the detailed grid in the areas of North Carolina.



Figure 11. ADCIRC Model Grid for North Carolina

Figure 12. Detailed ADCIRC Grid of Northern North Carolina





Figure 13. Detailed ADCIRC Grid of Central North Carolina

Figure 14. Detailed ADCIRC Grid of Southern North Carolina



Comparing Figure 9 of the northern area from the 2 NM grid of the effective and Figure 12 of the new surge modeling grid of the northern area as well as Figure 10 of the New Hanover effective surge model grid and

Figure 14 of the new surge model grid of the New Hanover area, emphasizes the amount of additional detail and accuracy the new surge modeling is adding to the coastal analysis.

3.4. Climatology

The same JPM statistical method was used for the effective study as with the new analysis for the tropical storms; however, an additional 25 years of storm climatology was added to the analysis. Figure 15 shows all the storms that have impacted the North Carolina coastline since 1980. Roughly 20 additional major hurricanes have impacted the North Carolina coastline since the previous effective surge study was completed (Figure 16), including tropical storms that have had major impacts in North Carolina, such as Irene and Isabel. While not all these storms are simulated as they occurred for a validation storm, they are used in the JPM analysis and their storm parameters are accounted for in the probabilities.



Figure 15. Storms that Impacted North Carolina Since 1980



Figure 16. Major Tropical Storms that Impacted North Carolina since 1980

For the extra-Tropical storms a different analysis was performed for the effective study versus the new analysis. The effective analysis was based on the extra-tropical storms that impacted a gage to the north of the state (in Hampton Roads, Virginia), where the impact and occurrence of extra-tropical storms is greater than in North Carolina. The new study uses those extra-tropical storms that have actually impacted North Carolina in the past, as described above. The effective analysis for extra-tropical storms was based on a statistical tide gage analysis in the coastal Virginia area, then the water elevations from that gage analysis were correlated to the North Carolina coast.

The storm surge models are forced with wind and pressure fields that represent each synthetic storm from the JPM analysis and each historic extra-tropical storm. The wind and pressure fields have to be developed for input to the ADCIRC model as part of the study. In the effective study the wind and pressure fields for tropical storms were developed through a model created in 1971 and based primary on a large sample of observed storms. The National weather Service later updated and published the methodology and model in 1979 and is referred to as NWS-23. In the last few decades, the measurement data from storms has greatly improved the understanding of the physics and characteristics of tropical events, hence the new coastal study uses the present industry standard in tropical wind and pressure field modeling, called the Hurricane Boundary Layer Model (HBL). The HBL model is more of a physics based model than the old NWS-23 model, hence is more suitable for a wide range of storm characteristics.

As discussed above, extra-tropical storms are modeled in the new coastal study exactly as they have occurred in history and they were not modeled in the effective study. The wind and pressure fields for extra-tropical storms are developed to precisely mimic the field measurements recorded during the storm event. The process of developing these extra-tropical wind and pressure fields is known as the Interactive Kinematic Objective Analysis (IOKA) method. The method requires manual refinement of the wind and pressure fields of extra-tropical storms to produce accurate hindcasts of these storms. After the manual adjustments, the Planetary Boundary Layer (PBL) model is used to create the wind and pressure fields for the extra-tropical storms.

4.0 Surge Results

The changes in the storm surge results from the effective study vary throughout North Carolina, depending on the geographic location. As discussed above, there are many differences in the data that was used for the studies, as well as many improvements to the overall study methods and procedures. Figure 17 shows the differences between the effective and new storm surge results for the 1-percent-annual-change values. One of the largest contributors for the differences is the great improvement in the level of detail captured by the new storm surge modeling grid versus the effective study.



Figure 17. Differences between Effective and Updated 1% Storm Surge Elevations

In the Pamlico Sound north of Cape Lookout decreases are due mainly to the size of the model grid. With the finer grid, the new modeling is able to capture the hydrodynamics of the Pamlico Sound and Albemarle Sound much more accurately. The inlets and barrier islands are better defined in the new model, and it is better able to capture the exchange of surge from the ocean into the sounds in greater accuracy as well. The effective model essentially formed a wall around the bays, resulting in the surge piling up against a fictitious

wall. In the new model the grid extends inland to high ground and up the rivers so that the surge is allowed to fill in all the estuaries to the west and north before piling up.

The sound areas south of Cape Lookout are much smaller than to the north, hence the storage capacity of the surge is much lower. This causes the surge to pile up in the sounds, and results in higher storm surge elevations than in the north where the surge in the bays is allowed to spread out over a greater area. In addition to the smaller sound areas, the east-west orientation of the coastline of Carteret County and Brunswick County make them more prone to higher surge elevations.

Additionally, with the more detailed modeling of extra-tropical versus the tide gage analysis from the effective study the areas in the north could be showing decreases due to the reduced effects of extra-tropical storms versus where the tide gages used in the effective are located. Extratropical storms are contributing a small amount to the combined statistical surge water levels for areas south of Cape Hatteras.

As mentioned previously the more accurate representation of wave setup by use of the 2-D wave model SWAN versus the effective empirical formula is reducing the overall total surge levels along the open coast areas. The wave setup values in the effective study were higher in the north than in the south, hence greater reduction to the surge elevations will be seen north of Cape Hatteras along the open coast. Wave setup also is at its highest on the ocean side of the barrier islands due to the large ocean storm waves breaking.

Also, if the barrier islands have ground elevations high enough to block the surge from overtopping the dunes, there could be large differences between the ocean side and bay side surge elevations. The efficiency of the inlets also becomes a factor, regulating how much surge is allowed to fill into the bays from the ocean. For instance, Beaufort Inlet due to it being a maintained deep channel allows for more efficient exchange of water between the ocean and inland sound and up the Newport River. Due to this, higher surge elevations will be found near inlets and lower values behind the barrier islands (Figure 18).



Figure 18. 1% Storm Surge Elevations near Beaufort Inlet

For the City of Jacksonville the effective model grid in Stones Bay was cut off before reaching the City of Jacksonville and then extending up the New River. The narrow pass at Pollocks point within the New River is 1000 feet wide. With a 6000 feet model grid in the effective versus the newer 300 foot grid, (see Figure 19) in the new study the surge propagation up the New River up to Jacksonville is much more accurate. Furthermore, the effective model grid is much coarser and less detailed than the new model grid in the area of Jacksonville (see Figure 20). The effective model did not extend up the New River, and poorly represented the physical geography with only one elevation per grid element of roughly 6,067 by 6,067 feet compared to the newer 300 foot grid.

Figure 19. ADCIRC Model Grid in New River



Figure 20. ADCIRC Grid vs. Effective Model Grid near City of Jacksonville



5.0 Transect Analysis Comparison

Transects are where detailed wave height analysis are performed to calculate the wave propagation over land, and are used to determine the base flood elevations for mapping the coastal hazards. Wave runup calculations are also made in the new study on each transect where the surge intersects the ground near the shoreline, as well as at natural vertical or manmade structures. Transect analyses depend on the ground elevation profile and the surge elevation profile for wave height depth calculations using the WHAFIS model. Storm induced dune erosion is analyzed before the profile is used in the WHAFIS model. The surge elevations are extracted from the surge model at each ground elevation point in the profile, making a variable surge surface as the transect moves inland. Figure 21 shows the overall differences in quantities of transects in the new study compared to the effective for the state of North Carolina. There are several inland bay counties that are getting new detailed wave height analysis and mapping for the first time, highlighted in yellow in Figure 21. These counties will see newly mapped AE Zones and the addition of VE Zones. An example of the new transect layout compared to the effective in Carteret County is shown in Figure 22 and Figure 23.



Figure 21. New Study Coastal Transects



Figure 22. Southern Carteret County Transects

Figure 23. Northern Carteret County Transects



On the sound side of barrier islands reverse transects are used to model the risks of wave hazards from winds blowing across the sounds in the offshore direction. These reverse transects are generally used where there are large sounds between the mainland and barrier islands. In North Carolina reverse transects are mainly used north of Cape Lookout (see Figure 24). Only Dare County had previously used reverse transects.



Figure 24. Reverse Transects

Another new component to the transect analysis not included in the effective studies is wave runup. Wave runup is particularly relevant to coastal flood levels in inland bay areas where the shorelines are relatively high and steep, and the bay is large enough to support wave heights over three feet. Wave runup mapping is characterized by VE Zones with single BFEs representing the maximum height wave runup that can be achieved up a slope. The BFE can vary from transect to transect due to the varying geography and profile

shape. Figure 25 shows an example of an area where wave runup was calculated and mapped.



Figure 25. Wave Runup Analysis and Mapping

6.0 Combined Probability of Coastal and Riverine Flooding

When rainfall riverine flooding areas and coastal flooding areas intersect and overlap a special analysis is performed. Since this overlapping area has both a probability of flooding from a rainfall event and a probability of flooding from a coastal storm event, the probability of any flooding level increases. This analysis can only be performed where the coastal flooding has no wave height impacts, only storm surge flooding. This combined probability analysis is accomplished by adding the riverine and coastal frequencies of each flooding level (see Figure 26). The new combined 1% flooding level is then mapped. There are 9 effective counties in North Carolina where the combined probability was used (see Figure 27). All Counties with detailed riverine flood studies that overlap with coastal flooding areas now have the impacts of combined probability considered in the regulatory BFE. An example of the results of a combined probability for Shallotte Creek is shown in Figure 28. This is a typical scenario where the coastal flood level will start out dominating the downstream areas of the stream, then as the flooding levels of coastal and riverine equal each other the combined probability analysis will apply the highest BFE from either. Going upstream the combined flooding level will move closer to the riverine level until the coastal flooding effects are subordinate to the riverine level.



Figure 26. Coastal/Riverine Combined Probability Example

Figure 27. Effective North Carolina Counties with Coastal/Riverine Combined Probability Analysis





Figure 28. Shallotte Creek Coastal/Riverine Combined Probability Results