1974

STORM SURGE SHOALING CORRECTIONS ALONG THE EAST COAST

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Study for
Federal Insurance Administration
U.S. Department of Housing and Urban Development

by

National Oceanic and Atmospheric Administration
U.S. Department of Commerce

December 1974

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1. Introduction

This study was done on a reimbursable basis by the National Oceanic and Atmospheric Administration (NOAA) for the Federal Insurance Administration (FIA), Department of Housing and Urban Development (HUD Interagency Agreement IAA-H-19-75, dated 10-10-74). The work was performed in the Techniques Development Laboratory (TDL), Systems Development Office, National Weather Service (NWS) with some input data supplied by the Office of Hydrology, NWS. This development work is designed to improve and extend a technique for estimating flood potential. This report is a follow-up to an earlier report [1]* on "Storm Surge Shoaling Corrections Along the Gulf Coast" prepared for FIA.

NOAA has an operational storm surge model, SPLASH (Special Program to List Amplitudes of Surges from Hurricanes). SPLASH numerically solves the linearized transport equations of motion in a curved parallelepiped basin, truncated from the ocean. The curved coastline is assumed to be a vertical wall and the remaining three surface boundaries are open to the sea. Initially, the sea in the basin is assumed at rest. Driving forces from the storm are applied on the water surface; also, a time history formulation of the bottom stress is utilized.

SPLASH computes the sea-surface response to meteorological forces that give rise to storm surges on and along the coast; the assemblage of these coastal surges, for any given time, is called a storm surge profile. Storm parameters, either from forecast or from climatology, are supplied to SPLASH. These parameters are:

a. storm size (radius of maximum wind),
b. storm intensity (pressure drop, peripheral pressure minus the central pressure), and
c. storm track (vector storm motion, speed and direction).

In addition, landfall point is given to SPLASH to fix the proper basin for the program. The storm surges computed by SPLASH lead to an estimate of flood potentials at coastal areas.

The grid distance used in our numerical computations must be fine enough to portray not only the storm surge but also the driving forces of the storm. Due to computer limitations and economics of machine operations, it is impossible to consider an entire ocean as a basin. Except for the coast, open boundaries are therefore used for the model.

An integral part of the SPLASH model is shoaling corrections. Shoaling correction is defined as the ratio of the peak surge generated in a particular basin to that of the peak surge in a standard basin and for

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*Number in brackets refers to References.

the same storm. Standard basin and storm were defined in [1], and these will be discussed in section 4. A shoaling correction will revise computed coastal surges so that they will apply to alternate landfall points. This use of the shoaling correction is very important to FIA studies; because of this procedure only few computer runs are required in a study.

Computation of shoaling corrections involves the preparation of input data to simulate basins. Procedures for preparing basin data were discussed in [1], hence we will only present an outline here.

2. Summary of Procedures for Preparing Basin Data

The SPLASH model computes storm surges for a particular storm in a particular basin. A basin is described by two-dimensional depth fields in the horizontal, coastal boundaries, local and geographical references, and orientation. To acquire such data, we used National Ocean Survey marine charts of scale 1:400,000. The chart delineates coastlines, the continental shelf, depth contours in shallow water, and spot depths in deep water.

Figure 1, reproduced from [1], indicates the approximate positions of basin centers on the Gulf and East coasts used in the SPLASH model. The abbreviated location names are used in the computer exactly as shown in Figure 1. This shows the present extent of the model; extension to the New England coast will be made in the near future.

For this study, as in [1], we have added basins between the stations shown in Figure 1; i.e., basins are overlapped every 50 miles instead of every 100 miles. Geographical locations of all basins in the Gulf are shown in Table 1a. This revises some locations published in [1] Locations of basins on the East coast are shown in Table 1b. We have not identified the additional basins with new city names because we want to keep the number of reference cities to a minimum. It is important to the users of the program not to have many reference cities, in order that the proper city may easily be chosen for a particular landfall of the storm. An intermediate basin is used by the program when landfall point is greater than 25 miles away from the reference city. Basins for the East coast only are the subject of this report.

There are seven steps in preparing basin depth data, as follows:

(1) Draw smooth coastlines and isobaths on the marine charts.

The coastline is smoothed subjectively to eliminate small broken features; sharp curvatures along the coastline greater than the curvature of any storm are avoided. Smoothed depth contours are drawn and any abrupt changes between nearby grids are eliminated. We took special care to assure that the depth contours and coastline for an individual basin are consistent with neighboring basins.

Figure 1. Selected stations on the East and Gulf coasts of the U.S. used by the SPLASH operational model to indicate coastal positions of basins.

Table 1a. Geographical Locations of Basin Centers and Stations* on the Gulf Coast.

Basin Number	Reference Station	Latitude	Longitude
1	PT ISABEL	26 05N	97 10W
1.5		26 46N	97 20W
2	ARANSAS PS	27 28N	97 16W
2.5		28 06N	96 49W
3	MATAGORDA	28 30N	96 11W
3.5		28 50N	95 30W
4	GALVESTON	29 17N	94 47W
4.5		29 38N	94 10W
5	CAMERON	29 47N	93 18W
5.5		29 34N	92 36W
6	EUGENE ILE	29 28N	91 42W
6.5		29 09N	91 06W
7	GRAND ISLE	29 08N	90 07W
7.5		29 19N	89 28W
8	GULFPORT	30 11N	89 07W
8.5		30 19N	88 28W
9	PENSACOLA	30 17N	87 27W
9.5		30 24N	86 41W
10	PANAMA CTY	30 11N	85 49W
10.5		29 40N	85 13W
11	PANACEA	29 53N	84 24W
11.5		29 55N	83 41W
12	CEDAR KEYS	29 16N	83 14W
12.5		28 42N	82 50W
13	CLEARWATER	28 00N	82 49W
13.5		27 18N	82 35W
14	FORT MYERS	26 36N	82 14W
14.5		26 05N	81 47W
15	EVRGLD CTY	25 29N	81 16W

*These location abbreviations are exactly as used in input to SPLASH Program for basins 100 miles apart; i.e., the integer numbered basins. The additional basins were not identified by cities because we want to keep reference cities to a minimum.

Table 1b. Geographical Locations of Basin Centers and Stations* on the East Coast.

Basin Number	Station	Latitude	Longitude
1	MATCMB KEY	24 55N	80 39W
1.5		25 32N	80 18W
2	FT LAUDRDL	26 16N	80 05W
2.5		26 58N	80 05W
3	VERO BEACH	27 39N	80 21W
3.5		28 22N	80 31W
4	N SMYRNA B	29 00N	80 52W
4.5		29 40N	81 12W
5	JACKSNVLLE	30 22N	81 24W
5.5		31 05N	81 22W
6	OSSABAW IS	31 46N	81 04W
6.5		32 18N	80 31W
7	CHARLESTON	32 44N	79 51W
7.5		33 12N	79 12W
8	MYRTLE BCH	33 46N	78 47W
8.5		33 52N	78 07W
9	N RIVER IN	34 28N	77 27W
9.5		34 41N	76 38W
10	OCRCKE INL	35 04N	76 01W
10.5		35 33N	75 28W
11	NAGS HEAD	36 14N	75 46W
11.5		35 56N	76 00W
12	ASSATEAGUE	37 34N	75 36W
12.5		38 12N	75 09W
13	CAPE MAY	38 55N	74 58W
13.5		39 26N	74 20W
14	SEA GIRT	40 06N	74 02W
14.5		40 35N	73 36W
15	SHNNCK INL	40 47N	72 40W

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*These location abbreviations are exactly as used in input to SPLASH Program for basins 100 miles apart; i.e., the integer numbered basins. The additional basins were not identified by cities because we want to keep reference cities to a minimum.

(2) Set up a baseline and basin grid on the marine charts.

The boundaries of each curved basin were arbitrarily skewed into a rectangle with the coastline serving as the straight baseline of the new basin. A rectangle 600 x 76 miles is overlaid on the coastline with the long axis parallel to the coast and the landward side, called the baseline, as nearly as possible coincident with the smoothed, curved coastline (see Figure 2 of [1]). The grid lines are normal to the baseline toward the sea. This rectangle now defines the basin for purposes of the model, SPLASH. A 151 x 20 network of grid points with 4-mile spacings is established within each basin. Further definitions, constraints, and conventions are discussed in earlier reports [1, 2, 4].

(3) Read basin data from the marine chart.

Extract four sets of basin data from the marine chart. These are: distance of selected depth contours from the coast on each of 151 grid lines, distance of coastline from the baseline for 151 positions on the coast, grid location of various chosen cities on the coast, and the actual distance along the curved coastline for later comparison with linear distance along the baseline. Distances of discrete isobaths from the coast are the basis for ascertaining basin depths at grid points. Distances of coastline from baseline are used to transpose forces from curved basin to the rectangular grid. The use of locations of cities on the coast, and curved distances along the coastline, are discussed in [1].

(4) Extract raw depth data at grid points.

To form depth values at basin grid points, we plot the discrete isobath values along each grid line and interpolate for depths at grid points on each line. To get depth values at the coast, we extrapolate the depth curve to the coast for each grid line.

(5) Plot and analyze depth data for the basin.

After interpolating the depth values (extrapolating for the value on the coast) for all grid points (on all lines), we then plot depth data along each line as a function of grid lengths from the coast. The graph for plotting has depth as ordinate, and the baseline which is crossed by 151 grid lines is the abscissa. Next, we connect the depth field at discrete grid lengths from the coast and subjectively smooth out precipitous gradients and sharp curvatures. In the analysis, consistency between contiguous basins is maintained.

(6) Read depth data and punch on cards.

Depth values on a staggered grid scheme are input to the SPLASH model. After analysis of the depth field above, depth data on a staggered grid are read and punched onto cards.

(7) Check depth data.

Depth data are checked for errors before storing in the SPLASH program. Some of the checking procedures are done objectively (by computer), others subjectively [1]. After depth data are checked, they are ready for input to the model. The first run of SPLASH with the new data provides further checking of the data based on the quality of the output. In the SPLASH run, we print the entire depth field and reanalyze it manually. This is a quality control step in the procedures. All errors are corrected and necessary adjustments are made.

After doing the foregoing steps for depth data, and after analyzing the remaining data such as distances of coastline from baseline, we then have complete basin data for input to the model. Data for each basin as used in the SPLASH model consist of:

(1) The angle of the baseline clockwise from geographic North; latitude of the basin's center, used to formulate the coriolis parameter; the number of coastal cities for later print out; the alphanumeric names of the cities; and the grid line locations of cities on the coastline.

(2) The distance (η) of the natural coast from the baseline at each grid line crossing the coast.

(3) The oceanic depth at each grid point of the basin. Basin data will become a part of the program and will be used in computations and applications for that basin.

3. East Coast Basins

This study develops shoaling correction curves for the East coast of the U.S. By East coast we mean the coastline 50 miles SW of Matecumbe Key, Florida to 50 miles NE of Shinnecock Inlet, Long Island, New York. This stretch of coast covers a distance of 1500 miles. The center of basin 1 is at Matecumbe Key and basin 15 at Shinnecock Inlet. Primary basins are numbered from south to north, 1 to 15, spaced every 100 miles approximately. Fourteen secondary basins are spaced approximately midway between the primary basins, for a total of 19 on the East coast (Table 1b).

The basins in southern and eastern Florida have startingly different bathymetry than the rest of the east coast. The east coast of Florida to Vero Beach has a very narrow continental shelf. From Vero Beach northward, the continental shelf widens up to New Smyrna Beach, then the shelf width becomes constant to Jacksonville. North of Florida the shelf widens and becomes widest about 30 miles south of Ossabaw Island, Georgia. From Ossabaw Island the shelf narrows to Charleston South Carolina, widens for about half the distance to Myrtle Beach, then narrows to the area of Pamlico Sound. From Pamlico Sound, the shelf widens to Nags Head, then is about constant in width to Sandy Hook, New Jersey. Finally, the shelf becomes narrow again south of Long Island. The width of the continental shelf is the main factor in surge generations--the wider the shelf the bigger the probable hurricane surge.

Pamlico Sound, North Carolina, is a large body of water separated from the ocean. We design our basins here with coasts on the ocean side of Pamlico Sound, therefore the shoaling curve is inapplicable for Pamlico Sound. The shoaling curves are also inapplicable for the mouth of Chesapeake and Delaware Bays. Near Sandy Hook, the coastal curvature is very sharp (almost a right angle); SPLASH I is not valid in this vicinity. Similarly, computations are not valid for Long Island Sound. A sheared coordinate system, now under development, will be helpful in these areas, but will require a reformation of the shoaling curve.

The orientations of storm tracks with respect to the East coast is considerably different than the Gulf coast. Also, hurricanes are bigger and travel with greater speed along the East coast.

When basin data are compiled, various factors must be considered, e.g., orientation, location, curvature of coastline, and maintenance of consistency between basins. To satisfy these requirements, revision of basins is a standard practice in our procedures. Basins in the vicinities of Cape Fear, Cape Lookout, and Sandy Hook require careful simulations; the dynamics in these areas are so sensitive to storm parameters that the shoaling curve is only a qualitative guide.

We are very critical in preparing our basin data to satisfy the dynamic constraints of the model. We revise basins to get better readings of geography and not as convenient empirical calibrations.

4. Comments on Shoaling Curves and Corrections

A shoaling curve for both the East and Gulf coasts is derived from the ratio of the peak surge computed in a local basin to that of the peak surge computed in a standard basin. A shoaling correction curve in a particular basin indicates the change in the coastal surge envelope* as it is displaced by a change in landfall point. The change of the surge envelope is due to changes in the bathymetry of the continental shelf with respect to landfall point. In both computations, a standard storm and standard vector motion are used. Reference peak surges (scaled or normalized values) are computed by the SPLASH model with a standard basin, standard vector motion, and landfall at 30° N latitude. We define a standard basin whose continental shelf slopes linearly at 3 feet per mile, with a depth of 15 feet at the coast and whose coast is a straight line, i.e., depth varying in one dimension only. This standard basin may be considered as the mean depth field averaged throughtout the continental shelf of the Gulf and East coasts. We define the standard vector motion as one perpendicular to the coast with a speed of 15 mph from sea to land. Hurricanes, of course, ordinarily do not landfall precisely normal to the coast, but for the purpose of computing shoaling curves our approach is the most convenient. Another alternative is to compute shoaling curves for various track angles to the coast. The approach however would require voluminous amounts of data and staggering computer expense.

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*Envelope means the plot of the coastal high water heights during passage of a storm. Highest surges at various points along the coast don't occur simultaneously.

Storm surges are related to storm size (radius of maximum wind). Assuming everything else is the same, for the same maximum wind, the larger storm will give larger surges. Storm size is even more important for storms moving along the coast [4].

For convenience in our derivation of shoaling curves, we form the storm's pressure drop so that maximum winds are 100 mph; this wind is maintained for any storm size and also for latitude of real basins on the coast. We can follow this procedure because the storm model accommodates these parametric values [3]. In previous work, we found that peak surges along the coast depend only mildly on latitude, but to some extent on radius of maximum wind (storm size). We computed two reference peak surges under standard conditions, for two storm sizes, radii of maximum winds of 15 and 30 miles. These two peak surges are used to scale maximum surges computed with the same storms in real basins.

For surge generation, the shoaling curves locate sensitive areas on the coast due to the bathymetry; this is most useful for planning purposes. The curves can be used as a guide to the precision necessary in collecting and processing of hurricane climatological data. The curves suggest where we must be most careful with input meteorology.

The shoaling curves are most valuable for planning purposes when looking at the entire coastline of the Gulf or Eastern seaboard. If we consider a storm with unchanging parameters and with identical angle of attack to the coast at any landfall point, then it is only necessary to make one run with the SPLASH program for any landfall point; this is so because a shoaling curve will then tell us the potential peak surge along the entire coast. In fact, a shoaling curve will even do more; it also has the ability to tell us how the computed surge envelope will change as landfall point is varied on the coast. This capability of the shoaling curve is extremely useful; it saves a lot of computer time and manpower.

4.1 INPUT and OUTPUT of SPLASH program

The following INPUT variables are necessary to run the SPLASH program for preparation of shoaling curves:

a. landfall point - location on the coastline where the center of the storm will strike land;

b. radius of maximum wind - specifies storm size; in this study, either 15 or 30 miles;

c. pressure drop - the intensity of the storm which for a given storm size and latitude gives a maximum wind of 100 mph; and

d. vector storm motion - storm direction and speed; for this study, direction is always normal to the coastline and speed is constant at 15 mph.

Peak surge and envelope of high waters along the coast are the output of the SPLASH model. These peak surges and envelopes form the basis for deriving the shoaling curve.

4.2 Preparing shoaling curves

To produce peak surges for standard storms along the east coast, we made SPLASH runs on all 29 basins for two storm sizes: 15 and 30 miles radii of maximum wind. We then plotted the resulting peak surges. For each basin, we chose a minimum of three landfall points: at the center of the baseline, and 16 miles on either side of the center. In complicated locations, (e.g. Biscayne Bay, Cape Fear, Cape Lookout, and Sandy Hook) we made more runs to get better resolution for the shoaling curve. For landfall on either side of the basin center, the track was made normal to the true coastline.

In addition to the location of peak surges for each storm size, we successively plot a portion of the computed envelope on either side of the peak surge. Figure 2 is an example of the process. We plot only a portion of each envelope that is within about one storm radius on both sides of the peaks. We now hand draw an envelope of peak surges, that is, an envelope of surge envelopes. This is done separately for the two storm sizes. The final envelope of peak surges is an unscaled shoaling curve.

In Figure 2, some peak surges are not on the shoaling curve because subjective adjustments of the envelope were made considering the bathymetry of the continental shelf. If more runs of the SPLASH program were made at closer spacings along the coast, then higher peak surges would be computed on top of the envelopes that did not fit the shoaling curve. The shoaling curve was based on all individual envelopes as shown in Figure 2. Although some peak surges are not on the final unscaled shoaling curve, they helped determine the variation of the curve along the coast.

4.3 Preparing shoaling correction curves and shoaling corrections

The shoaling curve must be scaled locally for each basin if it is to be useful in the SPLASH model. We don't want to be constrained to peak surge values generated by standard storms only.

The peak surge computed for a standard storm along the coast is a function of the slope of the continental shelf. Hence if we scale the final envelope according to the peak surge generated by a standard storm in a standard basin, then we reduce the final envelope to a common denominator. We call such a scaled, final envelope a shoaling curve. Examples appear in figures 3a and 3b.

Figure 3a includes shoaling curves on the Gulf coast that were discussed earlier in [1]. Figure 3b shows shoaling curves on the East coast for both 15-and 30-mile storm sizes. The curved coasts are extended linearly for convenient display. The ordinate is the shoaling factor or potential (the ratio of peak surge on any point of the coast to that of peak surge on a standard basin).

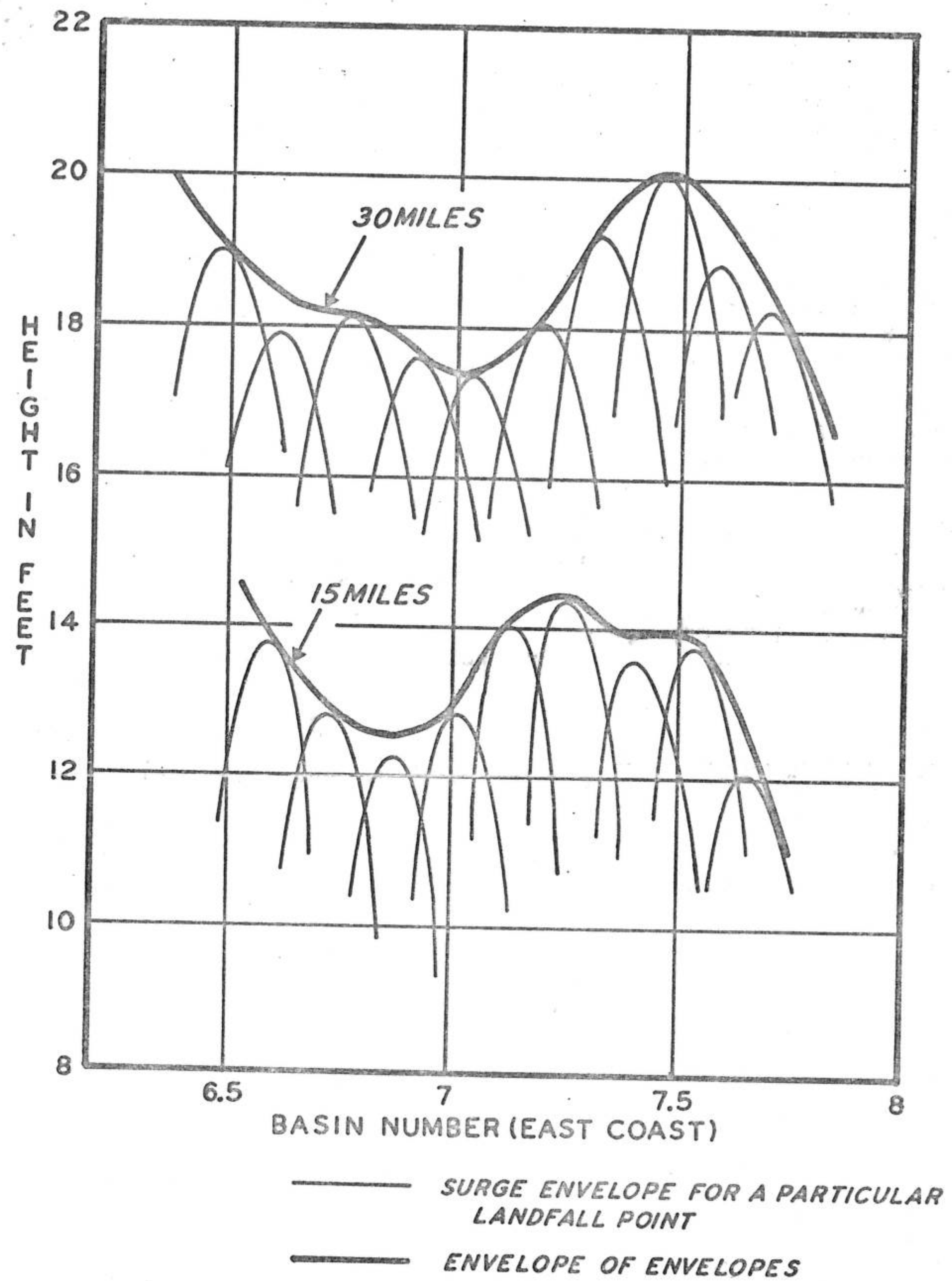

Figure 2. Analysis of the envelope of surge envelopes to arrive at shoaling curves. The upper envelope is for a storm size of 30 miles, the lower for a storm size of 15 miles.

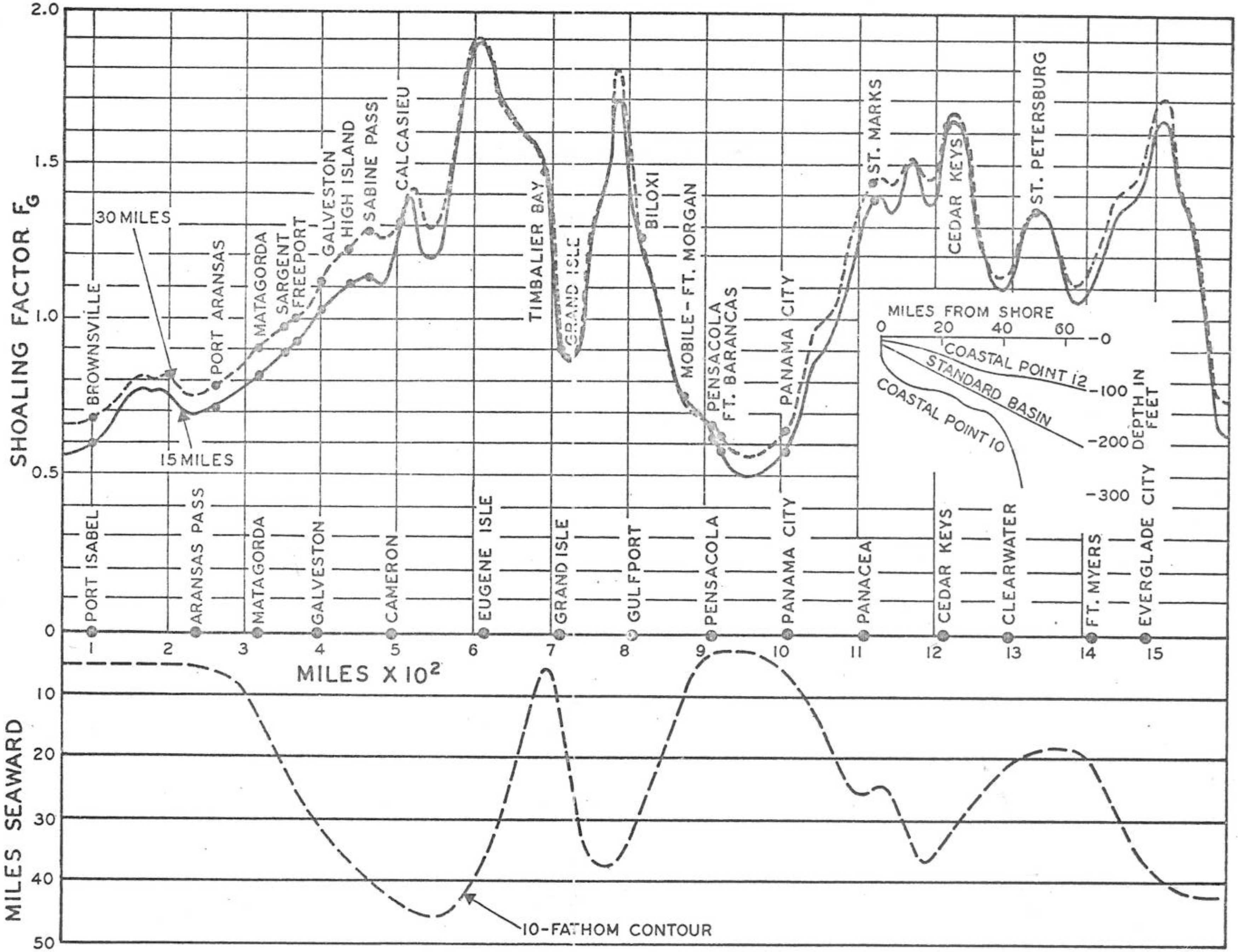

Figure 3a. Shoaling correction curves along the Gulf coast.

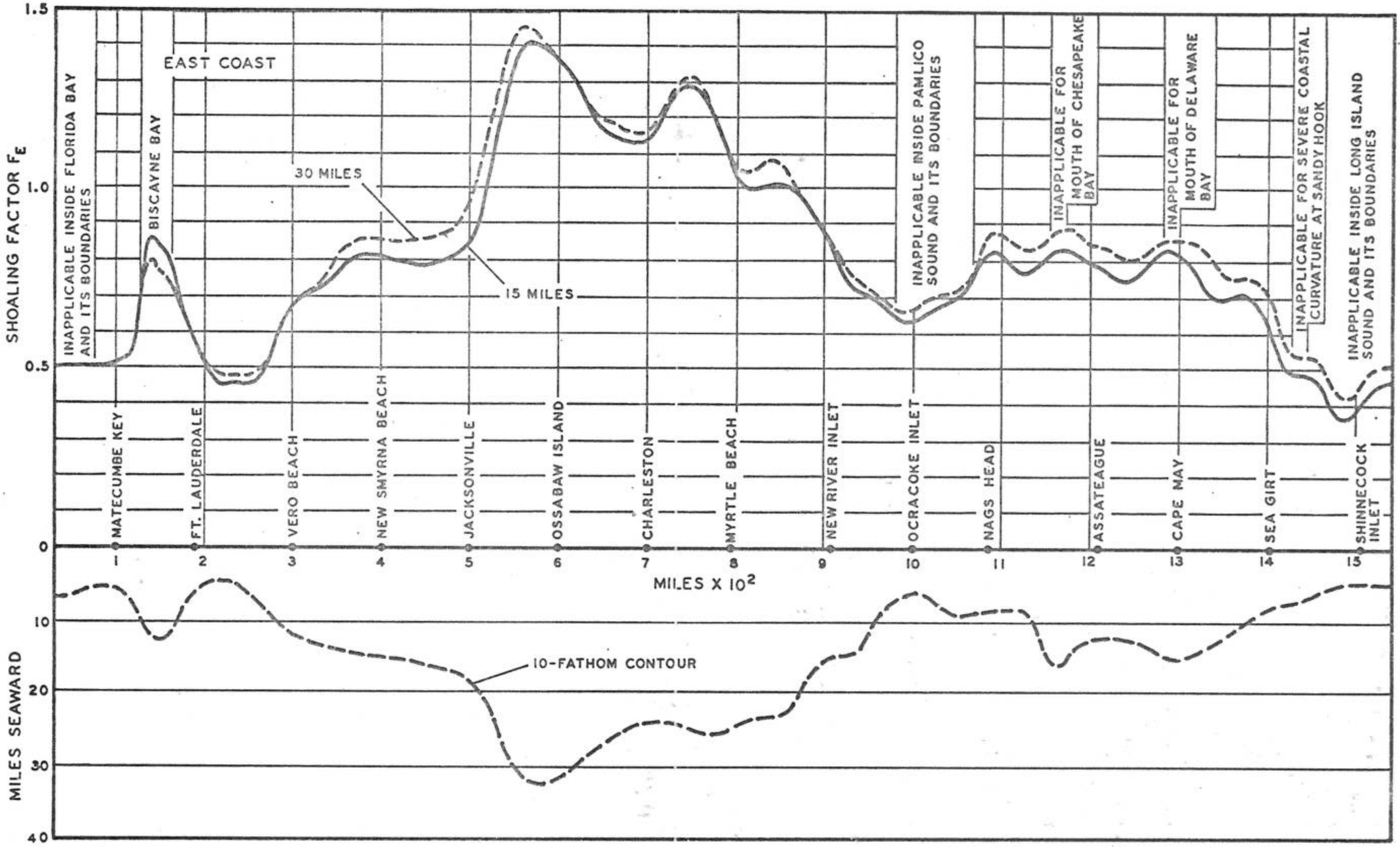

Figure 3b. Shoaling correction curves along the East coast.

The shoaling curve varies by a factor of about four on both coasts. The highest surge potential on the Gulf coast is higher than on the East coast for both storm sizes. We can conclude that for the same storm, the Gulf coast has higher storm surge potential than the East coast. However, we point out that storms are not necessarily the same on the Gulf and Atlantic shelves.

The two shoaling curves for the two storm sizes have been checked for consistency. Peaks and troughs coincide and the relative magnitudes are consistent. The peaks for a 30-mile storm size are generally higher than 15-mile storm size; this no doubt holds up to critical storm size in a given locale. In the Miami area, the critical storm size is probably closer to the 15-mile storm than to the 30-mile storm, thus the shoaling curve is higher there for the smaller storm size. The larger the storm size the smoother the shoaling curve.

There is a subtle dynamical effect in surge generation, related to bathymetry and storm size, that affects shoaling curves. In Figure 3, notice how the shoaling curve for the larger sized storm is shifted at times with respect to the shoaling curve of the small storm. To explain this shift, consider the case of depth contour lines on the continental shelf that are parallel to the coastline; for standard vector storm motion, the peak coastal surge occurs to the right of landfall a distance depending on storm size (observer on sea facing land). If, however, the depth contours are not parallel to the coast, then the position of the peak surge relative to landfall point is shifted. If the basin is shallower (steeper) to the right of landfall, the distance of peak surge from landfall point is larger (smaller) than storm size. This property of the shoaling curve is explained further in [2].

To correct a computed surge envelope for alternate landfall points, we have designed an individual shoaling correction curve for each basin. The basin shoaling correction curve is composed as follows:

1) Read Figure 3 the shoaling value at the center of the baseline of each basin.

2) Along the shoaling curve that corresponds to a given basin on the coast, divide the normalized curve values by the correction curve. Note the value of the correction is unity at basin center. Because the coastal distances represented by abscissa distances on Figure 3 are curvilinear, whereas the SPLASH model calculations are for equidistant coastal points, then the correction curve must be compressed to the linear lengths along the baseline.

After local shoaling corrections are computed, they are stored in the SPLASH program for instant use. The basin shoaling corrections are part of the basin data. The corrections operate on a computed surge envelope; if landfall point is hypothetically shifted on the coast, then the computed envelope is also shifted and operated on by the shoaling curve to correct for changing bathymetry.

The basin shoaling corrections are included in the SPLASH program for each of the 58 basins in the Gulf and East coasts. The program is used by the Office of Hydrology, NWS, NOAA, to compute outer coast surges with climatological input data for FIA flood projects. The shoaling curves in Figure 3 supersede the curves in Figure 2 of the SPLASH I manual, Technical Memorandum NWS TDL-46 [2].

5. Summary and Conclusions

Rising coastal waters are generated by hurricane driving forces. These forces are low atmospheric pressure (inverted barometer effect) and wind force. Thus a rotating mound of water forms under a storm in deep water. If the variable momentum in the sea (i.e. rotating mound of water or vorticity) is transformed into divergence, then storm surges are further generated. The bathymetry or sloping depths of continental shelf and the coastal boundary are effective mechanisms to transform vorticity to divergence.

NOAA has an existing dynamical-numerical model to compute storm surges, called SPLASH. To compute surges with this model, basin data are stored for all basins of the Gulf and East coasts of the United States. Basin data consist of depth values at grid points, orientation of the basin with respect to north, local and geographical references, and shoaling corrections.

Many subjective judgements are involved in preparing basin data and these judgements are based on long and involved experiments.

This paper outlines how the data are read from charts, analyzed, and prepared for storage in the computer program.

We numerically computed surge envelopes at equally spaced landfall intervals of 16 miles along a 1500-mile stretch of the East coast. In coastal areas where the bathymetry changes abruptly (i.e., Biscayne Bay and Miami area), we computed surge envelopes at closer intervals (every 8 miles apart) to obtain better resolution. At each landfall point, we made computer runs for two storm sizes. We then derived envelopes of peak surge to obtain shoaling curves. Finally, shoaling corrections were prepared for each basin in the SPLASH model.

The shoaling curves are used:

a. to compare the peak surge potential at one location to another along the Gulf and East coasts, provided the storm characteristics are the same;

b. for pointing out critical coastal areas to planners and developers;

c. for guiding climatologists in collecting and processing hurricane data; and

d. for giving meteorologists information on the isobathic effects on surge along coastal areas.

The shoaling correction curves, localized for each basin, are used even more extensively. In NOAA work for FIA, a shoaling correction curve is used to redefine the surge envelope for variable landfall points along the coast, without additional computer runs. Shoaling correction is very convenient for the frequency method of NOAA for estimating flood potentials on the outer coast. In studies for a coastal county, the outer coast tide frequency curve is based on many hypothetical hurricanes determined from hurricane climatology. Because of shoaling corrections, it is not necessary to run the SPLASH program with these storms at successive landfall points on the coast; it is only necessary to run the storm for one landfall point.

In operational use of SPLASH, we provide the forecasters with two additional surge envelopes based on landfall points 100 miles left and right of the forecast landfall. Additionally, the peak surges for the 600-mile long basin are included in the output. We are able to provide this extra information because of shoaling correction curves.

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