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On the Use of NOAA's Storm Surge Model, SLOSH, in Managing Coastal Hazards – The Experience in Puerto Rico

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Abstract. A numerical-dynamic, tropical storm surge model, SLOSH (Sea, Land, and Overland Surges from Hurricanes), was originally developed for real-time forecasting of hurricane storm surges on continental shelves, across inland water bodies and along coastlines and for inland routing of water – either from the sea or from inland water bodies. The model is two-dimensional, covering water bodies and inundated terrain. In the present version available at the University of Puerto Rico a curvilinear, polar coordinate grid scheme is used. The grid cells are approximately 3.2 × 3.2 km in size.

The model has been used in a revision of all coastal Flood Insurance Rate Maps (FIRM) for Puerto Rico and the U.S. Virgin Islands, and in hurricane evacuation studies. The FIRM's, since they are based on the 100 year stillwater elevation, are also used by the state Planning Board for regulatory purposes. The hurricane evacuation studies are used by emergency planners and personnel to assign shelters, escape routes, and delimit coastal zones that need to be evacuated during a hurricane threat.

Recently, the acquisition of data from hurricane Hugo has allowed the first comparison of model results and observations for Puerto Rico and the other islands.

Key words. Storm surges, Puerto Rico, SLOSH model, Hurricane Hugo, coastal hazard.

1. Introduction

A numerical-dynamic, tropical storm surge model, SLOSH (Sea, land, and Overland Surge from Hurricanes) was originally developed for real-time forecasting of hurricane storm surges on continental shelves, across inland water bodies and along coastlines and for inland routing of water – either from the sea or from inland water bodies. It allows for overtopping of barriers such as levees, dunes, spoil banks, and roads. The model is two-dimensional, covering water bodies and inundated terrain. In the present version available at the University of Puerto Rico a curvilinear, polar coordinate grid scheme is used.

The model, developed by Dr C. Jelesnianski and Dr J. Chen, of the National Oceanic and Atmospheric Administration, is the one presently being used by the National Hurricane Center, Miami, Florida, for storm surge warnings and hurricane evacuation studies all over the eastern seaboard of the U.S. It was brought to Puerto Rico mainly as a result of a Flood Insurance Study (FIS) funded by the Federal Emergency Management Agency. In this FIS, conducted at the Department of Marine Sciences of the University of Puerto Rico under the monitoring of the Department of Natural Resources of the Commonwealth of Puerto Rico, all the coastal flood maps were revised using the results of SLOSH based on the so-called Joint Probability Method. Basically, in this methodology hundreds of SLOSH simulations (and thousands of interpolations based on the SLOSH runs) were combined with the probability distributions determined for the storm's characteristics in order to produce a curve showing the stillwater elevation vs. return period at all points along the coastline, including land grid cells which are flooded by the surge. On top of the 100 and 500 year stillwater elevations determined by this methodology, wave action and runup effects were superimposed in order to define the coastal high hazard zone.

2. Brief Description of the SLOSH Model

A region modeled by SLOSH is referred to as a 'basin'. This basin must be sufficiently large to encompass a smaller region of interest, such as a bay. In the version presently available at the University a continuously expanding polar grid allows for a fine mesh in primary regions of interest, with continuous stretching to coarse mesh in deep waters or areas of lesser interest.

The surge model contains a storm wind model. For a computational run with a given storm event, a user supplies simple, time-dependent, meteorological storm parameters. These are:

(1) Latitude and longitude of storm positions, at 6 h intervals, for a 72 h track.
  (a) Beginning 48 h before the storm's nearest approach to a given reference point, and
  (b) ending 24 h after nearest approach.

In most cases only a segment of the 72 h track (at least a 30 h segment) is used in computations. The length and position of the truncated track segment depends on storm speed, distance of storm to the nearest approach, storm size, etc.

(2) Storm central pressure at 6 h intervals.

Wind is not an input parameter. The model storm computes a vector wind determined by balancing forces according to meteorological input parameters. In addition, the initial height of the water surface is required well before the storm directly affects the area of interest, e.g., the mean sea level if gage readings show no anomalous heights several days before storm arrival.

The SLOSH model does not require input boundary values with time. Boundary values are set by the storm itself or computed by the model. Boundaries are placed far from the primary area of interest to minimize their effects. Geographical and bathymetric data for the entire basin must be supplied by the modeler. One needs to ascertain barrier elevations of levees, road heights, etc.

It should be emphasized that there is no calibration or tuning to force agreement between observed and computed surges at a given location. That is, the three empirical coefficients in the model, namely the wind drag, eddy viscosity, and bottom slip coefficients are universally set as best fit constants derived from historical storm events and do not vary locally nor are calibrated or tuned for a particular geographical area. It is probable that the coefficients are a function of differing storm parameters and basin characteristics; hence, the calibration of the model based on a single storm event within a basin is avoided since there is no guarantee that the same coefficient values will serve as well for alternate storms. This avoidance of fine tuning is specially important in places like Puerto Rico where – at least until the passage of Hurricane Hugo in September of 1989 – there was no historical storm surge data available. In places where such reliable data is available one can use this data not for fine tuning the empirical coefficients mentioned above, but for making corrections to the basin data, i.e., bathymetry, topography, barriers location and/or elevation, etc. That is, the experience with the SLOSH model has shown that whenever observations strongly disagree with the results of the model there is a strong likelihood that the blame is on wrongly specified hydraulics of the site (i.e., width of channels and entrances to bays, erroneous barrier heights, depths, etc.), or wrongly specified storm parameters.

The output from the model consists of:

(1) The maximum stillwater height computed at each grid point regardless of the time when the maximum occurred, called the surface envelope of the highest waters.

(2) Starting 9 h before, and ending 9 h after the time of the nearest approach 'snapshots' are produced of the surge height. By this is meant the instantaneous value of the surge height at that point in time at each cell. Before, and up to the time of the nearest approach, the snapshots are given at 3 h intervals. After the nearest approach, and for the following 6 h, the snapshots are given every 2 h, with a final one 9 h after the nearest approach.

(3) Finally, for each of 60 selected coastal sites, time histories of the surge height, wind speed (10-min average winds) and direction are output. These start at least 18 h before the nearest approach and last 12 h after the nearest approach. These values are given at 10 min intervals.

The present version of SLOSH at the University of Puerto Rico does not consider: (1) wind generated waves, (2) rainfall flooding, (3) astronomical tidal effects, (4) river flooding effects.

If accurate input data is available for a storm's track, intensity, and size, it has been shown for many U.S. storm events that the computed surges are within ±20% of observed water levels (Jarvinen and Lawrence, 1985). Possible sources of error are:

(1) Noise in surge observations, often exceeding ±20%.
(2) The bathymetry given to SLOSH is not accurate.
(3) The topography given to SLOSH is not accurate.
(4) Errors in the initial water height.
(5) Wind wave effects, astronomical tidal effects, storm rainfall, and riverine flooding. These effects are often included in observed high water mark data used for verification.
(6) Noise in observed meteorological parameters. Sometimes it is the storm track which is a source of error. This is specially true if one uses the smooth track published after the event.

Jarvinen and Lawrence (1985) found a mean error of −0.09 m The mean absolute error was 0.43 m, and the error range was from −2.16 to 2.68 m. The standard deviation was 0.61 m. Seventy-nine percent of the errors fell within one standard deviation of the mean error; 97% fell within two standard deviations; and 99 fell within three standard deviations.

3. The Application of the SLOSH Model to Puerto Rico and the U.S. Virgin Islands

Puerto Rico and the U.S. Virgin Islands form part of the chain of islands outlining the northeastern boundary of the Caribbean Sea. Figure 1 shows the area encompassing the Puerto Rico SLOSH Basin together with a schematic illustration of the SLOSH polar grid coordinate system used. The origin of the polar coordinate system is located, at 30° N, 66° W. The distance of the polar grid origin to the top boundary of the basin is 1233.5 km, and to the lower boundary is 1416.5 km. Hence, the radial, or north-south extension of the basin is 182.8 km, and this was discretized into 55 cells. The radial width of the cells increases from 3.1 km at the top boundary to 3.5 km at the bottom one. Along the north coast of Puerto Rico it is 3.2 km and along the south coast it is 3.4 km. This relatively large cell size (large relative to the extremely narrow insular shelf) is due to having the polar origin so far away from the area of interest. The zonal extension is from Mona Island (a small island lying approximately 44 km west of Puerto Rico) in the west to the island of Anegada in the east. The top boundary is 383.8 km long and the bottom one is 441.3 km. Since there are 124 cells along the zonal direction then the zonal length of each cell is ≈3.2 km. Therefore, the cell size is approximately $3.2 \times 3.2\ \mathrm{km}^2$. The total number of grid cells is 6820.

The island of Puerto Rico is approximately 160 km long, and 56 km wide. Topographic information was obtained from the U.S. Geological Survey charts at a scale of 1:20000 and bathymetry from NOAA nautical charts. For both sets of maps (bathymetry and topography) overlays were made showing the outline of the cells. The overlays were placed on top of the corresponding maps and the average depth, or terrain height, was determined and given as an input to the

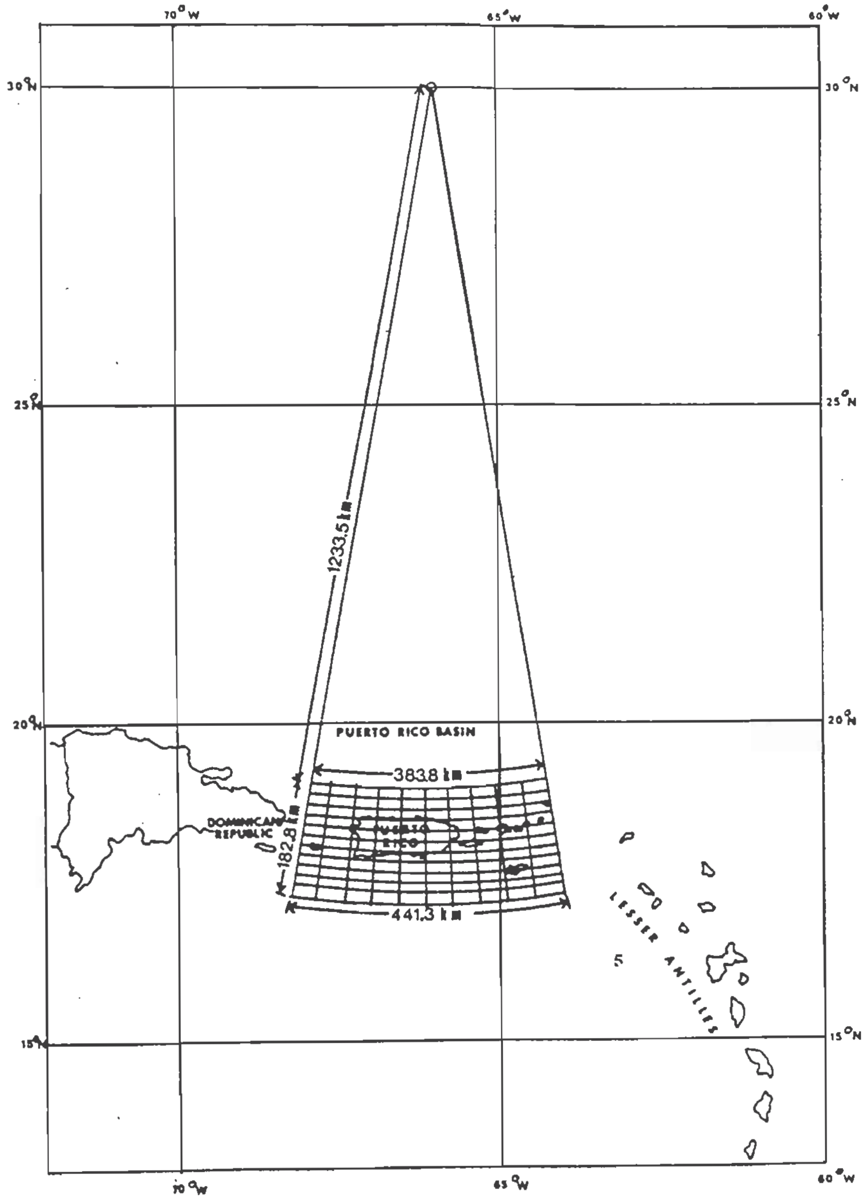

Fig. 1. Puerto Rico SLOSH Basin.

SLOSH model. The model accepts as input a lot of additional information. For example, if the separation between two islands is less than a grid cell then a channel, or choke is given at that place with a given depth, width and orientation. Much more details are given to the model in order to represent, as realistically as possible, anything that might alter the flow of water from one cell to another.

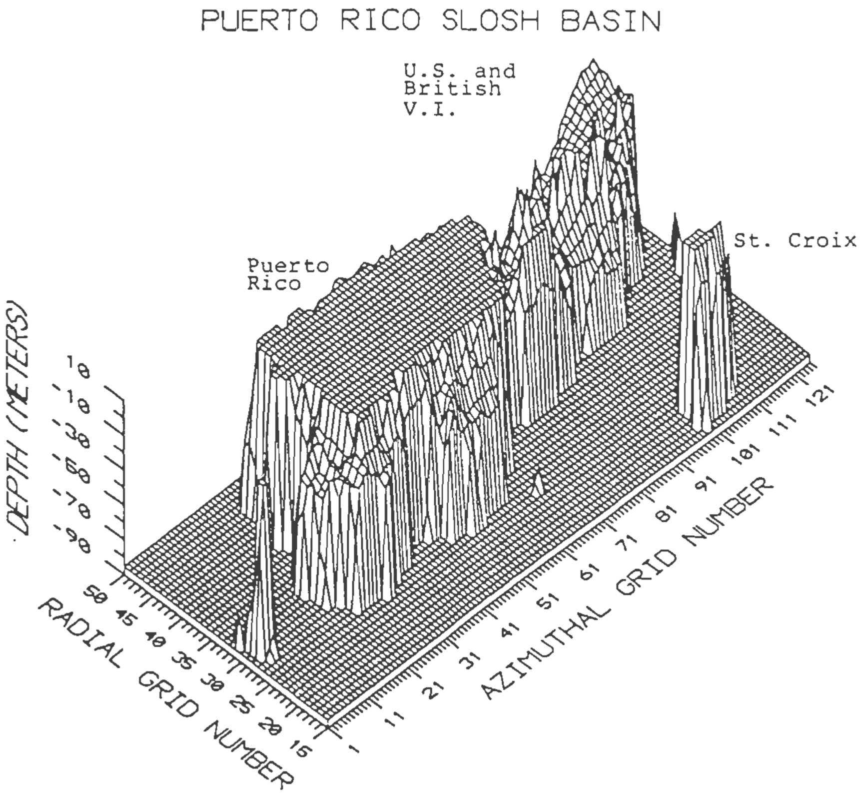

Fig. 2(a). Surface plot of SLOSH bathymetry for the Puerto Rico Basin. View from the southwest.

As mentioned above, Puerto Rico has an extremely narrow shelf, specially along the north coast. The shelf width varies between 1 and 3 km over more than half the coastline. Figure 2a, b shows a three-dimensional plot of the bathymetry given to SLOSH looking from the southwest and northeast, respectively. All terrain above mean sea level has been set flat, and all cell depths larger than 85 m were set at 85 m (as far as the model is concerned, 85 m is deep water). The extremely narrow and deep shelf seen in the figures brings as a consequence that surge values along Puerto Rico's (see also St. Croix) coast will never reach the values found along the eastern seaboard of the U.S., but on the other hand, the island is much more exposed to wave damage.

For the island situation like ours, with narrow, deep, shelves, the so-called wave setup contribution can become as important as – in some cases even more than – the combined wind and pressure setup. For islands surrounded by coral reefs there could also be the ponding effect on the landward side of the reefs due to wave breaking on the reefs. The possible combination of these two wave effects

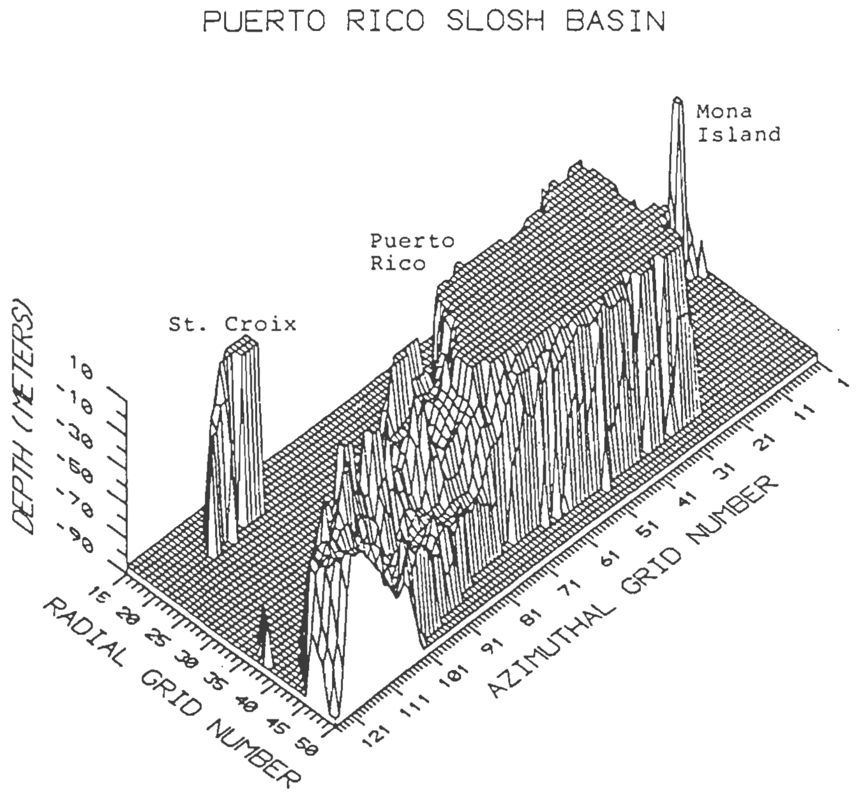

Fig. 2(b). Surface plot of the SLOSH bathymetry for the Puerto Rico Basin. View from the northeast.

is something that had to be considered since it can be as high as, or higher than, the wind and pressure setup. Unfortunately, quantitative estimates of these two effects are very difficult due to the complexity of the problem and the detailed bathymetry needed.

Wave setup and ponding estimates were made by the company Greenhorne & O'Mara, Inc. (Maryland, U.S.A.). They based their estimates on work done for the island of Guam, in the Pacific Ocean. Based on laboratory and numerical model results they concluded that for Guam and Guam-like islands, waves–in addition to wind and atmospheric pressure–must be accounted for when computing surges for strong hurricane conditions. Application of their findings to the Puerto Rico SLOSH Basin resulted in a wave setup/ponding contribution to the stillwater elevation of 0.82 m for the west, north, and east coasts of Puerto Rico, and 0.98 m for the south coast. For the smaller islands east of Puerto Rico, including the U.S. Virgin Islands, the estimated wave setup/ponding contribution varied between 0.98 and 1.37 m.

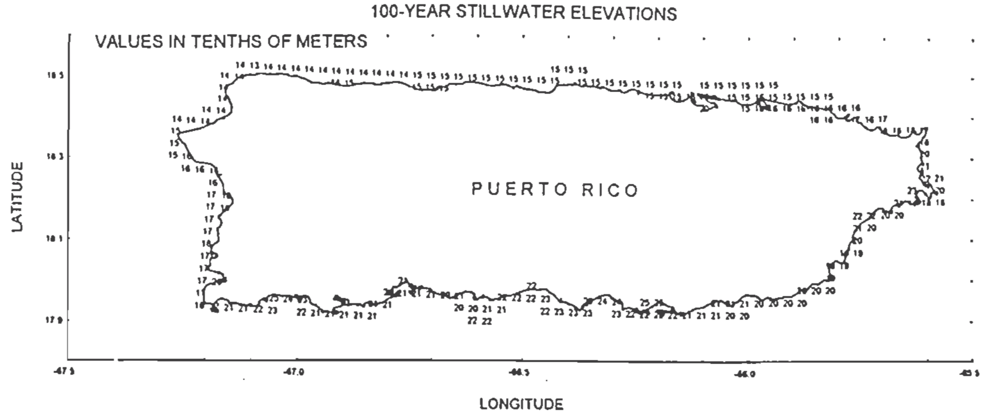

Fig. 3(a). Outline of the coastline of Puerto Rico, including the 100-year stillwater elevations (in tenths of meters).

3.1. *The Flood Insurance Study* (*FIS*)

The FIS done for Puerto Rico and the U.S. Virgin Islands was the first one ever done using the SLOSH model. The ultimate goal of the study was to produce the 100, and 500 year return period stillwater elevation around Puerto Rico and the U.S. Virgin Islands. The 100-year stillwater elevation estimates (including wave setup/ponding and astronomical tide) are shown in Figure 3a, b. The locations of the values outline the shape of the islands as seen by the SLOSH model. The exception to this are the few land grid cells which had such low elevations that they were flooded by the 100 year flood.

On top of these stillwater elevations high-frequency storm waves will propagate over flooded terrain and this wave action has to be estimated in order to define the high hazard zone width at any coastal site. These results are then used to revise the Federal Emergency Management Agency's Flood Insurance Rate Maps. These maps themselves are also used by the Puerto Rico Planning Board for coastal planning purposes and by the Department of Natural Resources in their evaluation of permits for sand extraction, establishment of coastal setback lines, etc.

For places in which historical data about events of this nature is almost non-existent, an accepted methodology for obtaining the above stillwater elevations with the given return periods is through the use of the so-called Joint Probability Method (JPM). This methodology has the following characteristics:

(1) The damaging phenomenon is produced by well-defined entities or events (storms, etc.) which can be parameterized, i.e., central pressure index, radius of maximum winds, speed and direction of translation.

(2) A physical model is developed which predicts the magnitude (and/or proba-

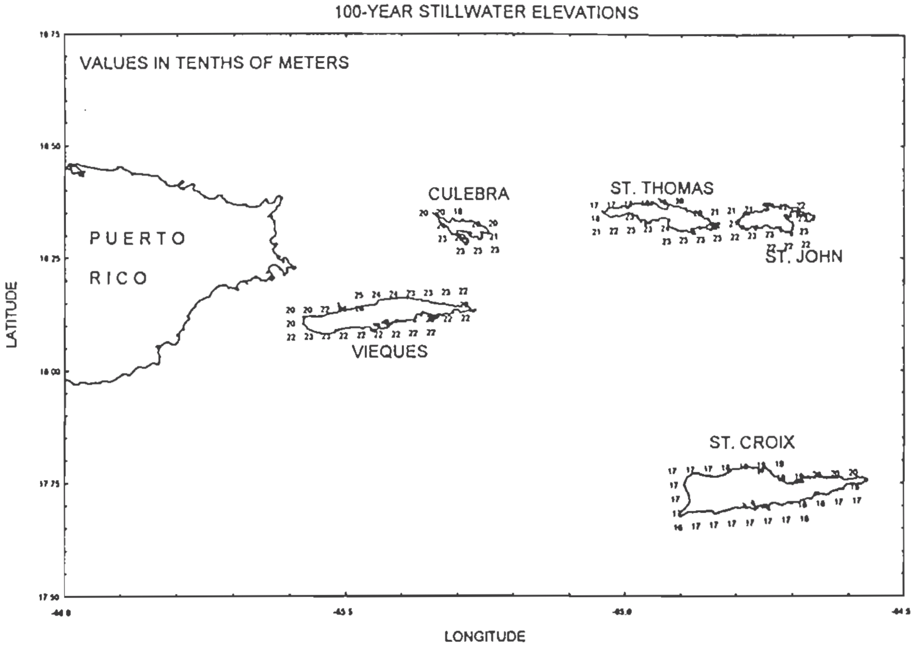

Fig. 3(b). Outline of the coastline of the offshore municipalities of Puerto Rico (Vieques and Culebra) and the U.S. Virgin Islands, including the 100-year stillwater elevations (in tenths of meters).

bility law) of the damaging phenomenon from the parameter values for the event.

(3) Historical data are used to predict the probabilities associated with the occurrence of various event intensities. This is usually expressed as the multivariate probability law for the parameters characterizing the event.

(4) The predictions from item (2) are combined with the probabilities from item (3) to obtain estimates for the site.

For a study of this nature it is necessary to make a very thorough statistical study of the tropical storm climatology around the area of interest. Ninety-nine years of storm data (obtained from the HURDAT tape supplied by the National Hurricane Center in Miami, FL) were analyzed. Five straight line storm headings were chosen for the study. For each one of these straight line tracks results were obtained for seven different central pressures, two storm sizes, and four different translation speeds. This gives a total of 280 possible combinations for each straight line track. The track separation was 10 nautical miles and the most distant tracks had to be such that the corresponding surge did fall below the 10 year surge for any given coastal site. This produced a total of 8456 simulations of which about 1300 were actual SLOSH computer runs. The rest of the simulations were obtained by interpolation of the actual SLOSH runs. Cumulative distribution functions were determined for the central pressure anomaly, radius of maximum winds, forward speed of translation, and storm heading. From these distributions probabilities of occurrence were assigned to each hurricane event and, consequently, to each storm surge elevation due to that given hurricane event. In this way the return period for different flood elevations was determined for each of the coastal water cells, and for each one of the coastal land cells which can be flooded by the surge.

The next step is the delineation of the high-hazard zone, that is, the strip of land near the shoreline where wave action and associated current velocities are bound to be such that no development should be permitted inside it, or if allowed, very stringent construction requirements are set. For this purpose use is made of two computer programs that simulate the landward penetration of storm waves. One such program simulates the propagation of waves over the flooded area and decreases the wave height according to energy dissipated by the obstacles the waves encounter. It also can increase the wave height if a sufficiently long fetch is encountered. The other program is a computerized version of the wave runup analysis that is performed on composite slopes (Hallermeier *et al.*, 1990). This phase of the study needs detailed site-specific bathymetric and topographic profiles in which dunes, vegetation, man-made obstructions, etc. are taken into consideration. Also, an analysis has to be made before the models are run of whether any of the obstacles (sand dunes, structures, etc.) can withstand the storm or not. If it is judged that they cannot then the analysis has to be made as if they were not there. Due to the detailed site-specific data needed for the delineation of the high hazard zone, this is being done at a slower pace and where of critical need.

3.2. *Hurricane Evacuation Studies Using SLOSH*

The main use being given to SLOSH nowadays in the U.S. and Puerto Rico is in hurricane evacuation studies. In this case SLOSH runs are made with hypothetical Categories 1 to 5 (according to the Saffir/Simpson scale) storms. Flood maps are produced for each category showing areas at risk (including population, number of cars, etc.), shelters (and their capacity), evacuation roads, and time needed to evacuate. The purpose of a study of this type is to provide emergency management officials with realistic data quantifying the major factors involved in hurricane evacuation decision-making. Generally these studies consist of several related analyses that develop technical data concerning hurricane hazards, vulnerability of the population, public response to evacuation advisories, timing of evacuations, and sheltering needs for various hurricane threat situations. The ultimate aim is not having to run SLOSH in real time, but have all the relevant results from the model available in case of a hurricane threat. Flood maps for the different hurricane categories have been prepared for sections of the south, east, and north (specifically, for the San Juan metropolitan area) coasts.

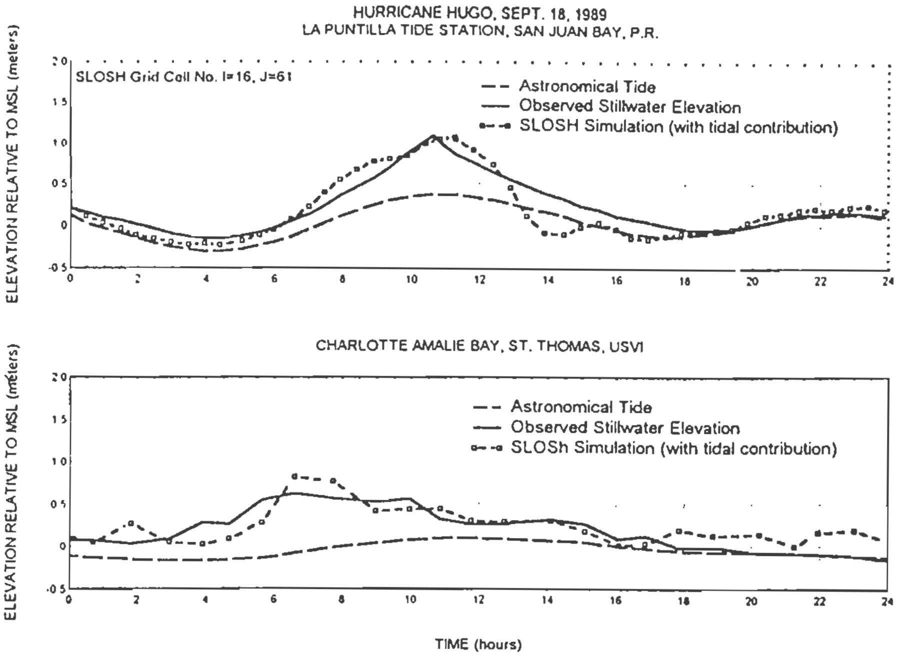

Fig. 4. Comparison of observed versus predicted stillwater elevations during the passage of Hurricane Hugo (Sept. 1989). Also shown is the astronomical tidal contribution. (a) At La Puntilla tide station, San Juan Bay, San Juan, P.R.; (b) At tide station inside Charlotte Amalie Bay, St. Thomas, U.S.V.I.

4. Hurricane Hugo – Comparison of Observations vs. Simulations

Hurricane Hugo (September 1989) passed near the U.S. Virgin Islands and Puerto Rico during 17–18 September 1989. During its passage through St Croix it was of category 4 (Cat 4) strength, weakening to a Cat 3 storm when it was nearest to the northeast coast of Puerto Rico. Maximum winds along the eastern coast of Puerto Rico were alongshore, or from land to sea, which helped to keep relatively low surge values and, consequently, no major coastal damage was observed. Along the eastern part of the north coast the maximum winds were from the north, which made them go from sea to land. But by this time the hurricane was of Cat 3 strength and Puerto Rico was on the left side of the track. Hence, the observed winds were not too strong.

Figures 4a, b show comparisons of SLOSH simulations vs. tide gauge observations inside San Juan (P.R.) and Charlotte Amalie (USVI, St. Thomas) bays. The sharp drop in the predicted surge (see Figure 4a) after the time of the maximum, where predictions become much smaller than the observations, can be explained as due to the fact that the SLOSH winds do not discriminate between winds from sea to land and winds from land to sea (which have been affected by the increased roughness due to the land). As a consequence, the SLOSH winds tend to overestimate the real winds when blowing from land to sea and, hence, drain the bay much faster than observed. Aside from this fact, the simulations tend to match the observations very well, within the ±20% found along the eastern seaboard of the U.S.

5. Conclusion

The use of computers to simulate the effect of tropical cyclones on the coastlines of Puerto Rico and the U.S. Virgin Islands is allowing coastal planners, insurance companies, and government agencies to better plan the development of our coastlines which, during the past two decades, have seen the highest growth in population. Results are being used for the determination of insurance rates, minimum requirements in the construction of coastal structures, coastal construction setback lines, erosion mitigation, and hurricane evacuation plans.

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