Water Level Statistics for Design of Transportation Facilities in Coastal Louisiana

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Results are presented of an effort to provide up-to-date information about hurricane flood water level statistics for coastal Louisiana that reflect present landscape conditions and to enable flood elevations to be easily updated in the future. The water level statistics presented are based on a hydrodynamic computer model to compute the threat of hurricane flooding within the coastal zone of Louisiana. Hydrodynamic models of flooding are currently used to determine flood water levels in rivers and channels. The hydrodynamic model used in this study is the overland flooding model of the Federal Emergency Management Agency, the same model used to compute the base flood elevations for the National Flood Insurance Program. The model has been modified to make it operate more easily on a microcomputer. The latest topographic data and hurricane statistics were used in the study.

Water level statistics for the design of transportation facilities in coastal Louisiana are needed because this area is subject to flooding by hurricane surges and is undergoing extensive natural and man-made alterations, which modify the extent of flooding. The use of historic flood levels is misleading in this case because the flood threat is changing with time. This report presents the results of work that provides up-to-date information about hurricane flood water level statistics for coastal Louisiana that reflect present landscape conditions. This work also provides the ability to update flood elevations easily in the future.

The water level statistics presented in this paper are based on a hydrodynamic computer model to compute the threat of hurricane flooding within the coastal zone of Louisiana. Hydrodynamic models of flooding are currently used to determine flood water levels in rivers and channels. The hydrodynamic model used in this study is the overland flooding model of the Federal Emergency Management Agency (FEMA). This is the same model used to compute the base flood elevations for the National Flood Insurance Program. The model has been modified to make it operate more easily on a microcomputer. The latest topographic data and hurricane statistics have been used in the study.

The statistics of the hurricane flood water elevations were defined for several average return periods, that is, 10, 25, 50, 100, and 500 years. These statistics were determined for locations referenced to Lambert coordinates using a joint probability analysis. In this analysis water levels are forecast for a variety of hurricane storms using the surge simulation computer model.

There has been no previous work on the use of computer model–derived hurricane flood statistics for the Louisiana Department of Transportation and Development (LaDOTD).

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OBJECTIVES AND SCOPE

The overall objective of the study was to develop flood statistics for coastal Louisiana that would reflect current landscape conditions in the state and that could be easily updated in the future. The flood statistics were to be used by LaDOTD in designing and maintaining transportation facilities. The flood statistics were to be defined over the coastal zone of Louisiana; they consist of the probability at a given location that water levels will exceed a given elevation during an average year. From these statistics, the water levels associated with average return periods of 10, 25, 50, 100, and 500 years were to be determined. The specific objectives of the study were to acquire the required input data, to calibrate and verify an appropriate computer model and to use the model to compute flood statistics and water levels for all areas of coastal Louisiana subject to hurricane flooding. A second objective was to transfer the flood prediction, in terms of the data bases and computer program, to LaDOTD for its own practical use.

The primary effort of the work was to establish a flood prediction capability and apply it to determine flood elevation statistics. The surge simulation model used in the study is the latest version of the FEMA surge model. This model was chosen because it was developed specifically to evaluate the threat of hurricane flooding in coastal areas by FEMA.

The data used to set up and test the model were taken from existing sources; no new data were taken for this study. Topographic data were taken from United States Geological Survey (USGS) topographic maps. Bathymetry was taken from NOS charts. Both of these map sets contain data of a variety of ages and accuracies. Some data were available from LaDOTD and other sources that allowed the map data to be updated. For many of the marsh areas of the coastal zone, no topographic data were available, and the elevations for these areas had to be estimated based on vegetation type.

The flooding model is numerically relatively simple; however, it has a great deal of flexibility built into it that makes it useful for engineering studies. The model uses an explicit, two-dimensional space-staggered, finite difference scheme to simulate overland flooding. The model computes water level and water velocity over a square spatial grid. The model incorporates initially unflooded land cells into the computation domain as they are flooded. Multiple grids are used in the computations and are nested to produce forecasts for small grid sizes. The grid size used in the computations was 3048 m. Inputs to the model included bathymetry and topography, shoreline geometry, atmospheric and storm pressures, boundary conditions, and bottom friction resistance coefficients. The modeling also included subgrid barriers such as islands, roadways, and levees, and subgrid channels such as rivers, bayous, and canals.

METHODOLOGY

The approach taken in this study was to follow the method recommended by FEMA for determining hurricane flooding statistics. The methodology is called the joint probability method (JPM). This method incorporates historical data on representative storm parameters. Statistical distributions of the storm parameters that affect flood levels are then developed. From these distributions, a large population of "synthetic storms" is generated. These storms are called synthetic because they resemble historical storms. They could have occurred but may not have been observed. The surge model is then used to determine the storm surge elevations produced along and inland of the coastline of interest for each of these storms. The JPM is used to infer the statistics of these surge levels from the statistics of the meteorological parameters that define the storm. An overview of the JPM follows.

Five storm parameters are used to define synthetic hurricanes. These are the central pressure depression, radius to maximum winds, storm forward speed, direction of storm motion, and storm track location with respect to the study area. These parameters define the surge-producing potential of a hurricane. Storm wind speed is a function of actual pressure, radius, and storm forward speed. The probability distributions of these parameters are derived from a statistical analysis of historical hurricanes that have affected the study area. These probability distributions are then divided into discrete intervals, with each interval represented by a single parameter value and an appropriate probability weight. The combination of all discrete parameter values represents a large set, or ensemble, of several synthetic storms.

The actual surge that each synthetic storm produces at a location is determined through detailed hydrodynamic modeling. It is important to realize that the accuracy of the JPM hinges on the use of a simulation model that accurately simulates the surges caused by hurricanes. The required simulation capability actually involves more than one model. One model is used to simulate the hurricane forcing on the ocean. This forcing includes wind stress and barometric pressure gradients. Both of these are defined around the center of the hurricane. Their magnitude and areal extent are determined by the central pressure depression and the radius to maximum winds of the storm. The second model is a hydrodynamic model for the area of interest. This modal simulates the surge produced by the atmospheric forcing. Surge generation, propagation, and transformation in shallow water are normally modeled using an offshore grid and an inland or nearshore grid.

The peak water-surface elevation that results from the combination of the storm surge and the astronomic tide depends on the magnitude of the astronomic tide and the phasing between the astronomic tide and the storm surge. Because of dynamic coupling, this combination is often nonlinear; that is, it is not possible to simply add the computed surge to the known astronomic tide.

The frequency of the storm, and hence the frequency of the storm surge elevation, is defined by the joint probabilities of the storm characteristics. This frequency is computed as the historical density of storms, in events per year per nautical mile, multiplied by the probability of a storm with specific characteristics. These characteristics include the radius to maximum winds, storm speed, central pressure depression, track angle, and storm track. The joint probability of these various parameters is evaluated as the product of the probabilities of each of the storm parameters. When these parameters are statistically dependent, conditional probabilities should be used. The combination of surge with tide is considered random; that is, the surge has an equal probability of occurring at any phase of the tide.

DATA COLLECTION

Data needed as input to set up and run the simulation model were acquired from available sources. The methodology for collecting and using the data needed in the study is described in the following sections.

Topographic Data

The topographic data used as input to the numerical calculations were based on USGS quad sheets, NOS bathymetric charts, and topographic data compiled by parishes and by the state.

The land topographic data was primarily based on 7.5-min and 15-min USGS quad sheets. The quad sheets used cover all pertinent areas of Louisiana, Mississippi, and Texas from 88 degrees west longitude to 96 degrees west longitude, and from 30 degrees 30 minutes north latitude southward to the shoreline. The quad sheets were the latest available and have dates ranging from 1934 to 1985, with most map dates ranging from 1970 to 1985. The maps contain contours at 1.52-m intervals and spot measurements to the nearest meter at scattered points. The datum of the quad sheets is National Geodetic Vertical Datum (NGVD) 1929. Additional data were taken from the USGS metric maps series 1:100,000. These maps contain information from topographic surveys during the period from 1971 to 1973.

The inland and offshore bathymetric data were based on NOS charts in the 1100 and 11000 series and quad sheets. The charts are at various scales and cover the same longitude limits as the quad sheets; they extend in a north-south direction from the shoreline to beyond the edge of the continental shelf. The charts are dated 1984, 1985, and 1986. These charts are also used to define the offshore bathymetry for the calibration simulations. The charts contain contours at 1.83-m intervals and a large number of spot water depths. The datum for the charts is Mean Lower Low Water. This datum differs from mean sea level by about .21 to .24 m.

The topographic data collected by parishes and by the state were also used in setting up the model. These data were located in the appropriate 7.5-min quad sheet being used to set up the model grid. The topographic data were augmented by using existing aerial photos and acquired satellite images that allowed the areal extent of the topographic features to be assessed.

The topographic data within each grid cell were averaged to determine the ground elevation value input into the model. Where topographic data were lacking, the grid cell elevation was assigned based on vegetation type. It is known that certain types of marsh plants occupy habitats where water level is at a fixed relation to the tidal datums. Most of the salt marsh areas of the state were taken as a few tenths of a foot above mean tide level. The mean tide level itself is at an elevation of about .15 to .31 m above the present NGVD datum. The datum for the recently surveyed topographic data is NGVD 1982, although some data refer to NGVD 1965. There is a problem with reconciling the various datums used for different data sets, because in Louisiana the benchmarks are sinking while sea level is rising and NGVD is being redefined. In this study all elevations refer to the 1982 NGVD.

Barrier and River Data

Barriers and rivers that occur in the coastal zone have a controlling influence on flood levels. Barriers include roadways, levees, and natural features such as cheniers. Rivers include channels, canals, and inlets. These features are typically much smaller in width than a grid cell, about 30.48 to 304.8 m wide. The information needed about barriers includes elevation, width, and roughness. Data were obtained for the subgrid scale landscape features of barriers and rivers from a variety of sources. The barrier elevations for the inland grid were taken from the maps used to determine topography. These maps contain selected elevations of the ground around the barrier crest. Additional information was obtained from USGS quad sheets, which contain elevations for benchmarks.

The river data were taken primarily from the NOS charts used for obtaining the bathymetric data. Additional data were obtained from the Corps of Engineers and from professional surveyors.

Hurricane Statistics

The source of the data and methods used to determine the hurricane frequency and parameter statistics was the work by Ho et al. (*1*), referred to herein as NWS86. The data base and methodologies presented in NWS86 were developed specifically for flood forecasting studies; therefore the present study closely followed NWS86 methodology. The NWS86 report presents data that describe the statistics of all of the hurricane storm parameters needed for this study.

The hurricane storm parameter statistics used in this study were taken from NWS86. These data from NWS86 were used to determine the cumulative probabilities for the hurricane parameters for various locations along the Louisiana coast. The readings were taken at various miles along the Louisiana coastline from the appropriate graphs and tables in NWS86.

The approach recommended in NWS86 was used to discretize the hurricane parameter probability distributions for use with the surge model. Representative probability ranges were defined for each parameter and the average value of the parameter in the range was computed and taken as the discrete value. The discretized hurricane distributions were determined for various mileages along the coast. Three discrete ranges were selected for pressure depression, and two for radius, forward velocity, and direction, and 14 for distance along the coast. The pressure was discretized into three ranges having average pressures of 936, 963, and 991 millibars. These ranges are consistent with the need to represent the lower pressures with higher resolution. The radius was discretized into ranges having average radii of 24 101.54 and 72 304.61 m. The forward velocity was discretized into 4.16 and 20.28 m/sec ranges. The direction was discretized into 140 and 205 degrees. This produced hurricane approach directions that were on both sides of 180 degrees. Each direction had a probability of 50 percent.

SURGE SIMULATION MODEL

The overland flooding model used in the study has been developed by FEMA to predict hurricane flood elevations for the National Flood Insurance Program. The model uses an explicit, two-dimensional spaced-staggered, finite difference scheme to simulate the surges caused by hurricanes. Inputs to the model include the bathymetry, coastline configuration, boundary conditions, and bottom friction and other flow resistance coefficients. Also required are the surface wind stress and atmospheric pressure distributions of the hurricane. The surge model simulates the surge elevations everywhere in the modeled region.

The hydrodynamic model uses the principles of conservation of momentum and mass to simulate the response of the ocean to hurricanes. The momentum equation represents a balance between inertial (acceleration) forces and gravity forces, wind stress, atmospheric pressure gradient forces, the reactive bottom friction forces, and the Coriolis acceleration effect caused by the earth's rotation. The model uses a rectangular grid to discretize the simulated region of the ocean. The grid is oriented with the y-axis parallel to the general trend of the coastline and the x-axis extending into the ocean. The top of the grid is located where ground elevations are above the expected maximum surge elevation or where the inland propagation of the surge through channels becomes negligible, or both. The model can also simulate the flooding of low-lying areas resulting from astronomical tides.

In this application of the model two grids were used. An offshore grid having spacing of 9144 m extended out to the deep water of the Gulf of Mexico and had lateral boundaries far removed from Louisiana. The purpose of this grid model was to simulate the storm surge generation over the deep ocean and the continental shelf. A second inland grid having a resolution of 3048 m was used to generate the surge elevations used in this study. It more accurately represented the nearshore geometry of the study area. The two grids were embedded such that the inland grid covers in more detail a portion of the offshore grid. Water surface elevations at the boundary of the inland grid are transferred from the offshore simulation.

Grids and Input Files

The offshore and inland grids were based on the Lambert plane coordinates (southern grid). The offshore grid was 100 cells east-west by 37 cells north-south and had a grid size of 9144 m, as shown in Figure 1. The grid extended from Lambert X = 400,000 on the west to Lambert X = 3,400,000 on the east, and from Lambert Y = 700,000 on the north to Lambert Y = −410,000 on the south. The grid lines were oriented along the lines of the Lambert coordinate axis. The inland grid was 170 cells east-west and 59 cells north-south, and had a grid size of 3048 m, as shown in Figure 2. The grid had boundaries of Lambert Y = 1,150,000 on the west and Lambert Y = 2,850,000 on the east. The northern border was Lambert Y = 670,000 and the southern boundary was Lambert Y = 80,000. The inland grid was separated into two halves during computations.

The topographic and bathymetric data for each grid were obtained from the maps and charts described previously. The average elevation for each 9144 m grid cell was based on averaging several readings over the grid. For the bathymetric data, the actual soundings within each grid cell were numerically averaged. In most cases there were several soundings per grid cell, with some grid cells having 30 to 40 soundings. For the land grid cells, the average elevation was based on nine separate elevations: the center, four corners, and four boundary midpoints. Where survey data were available they were averaged for a 3048-m grid cell and used to adjust the grid cell average value obtained from the quad sheets. The 3048-m grid averages themselves were averaged over a 3048-m grid and were used for the offshore grid. The offshore grid was

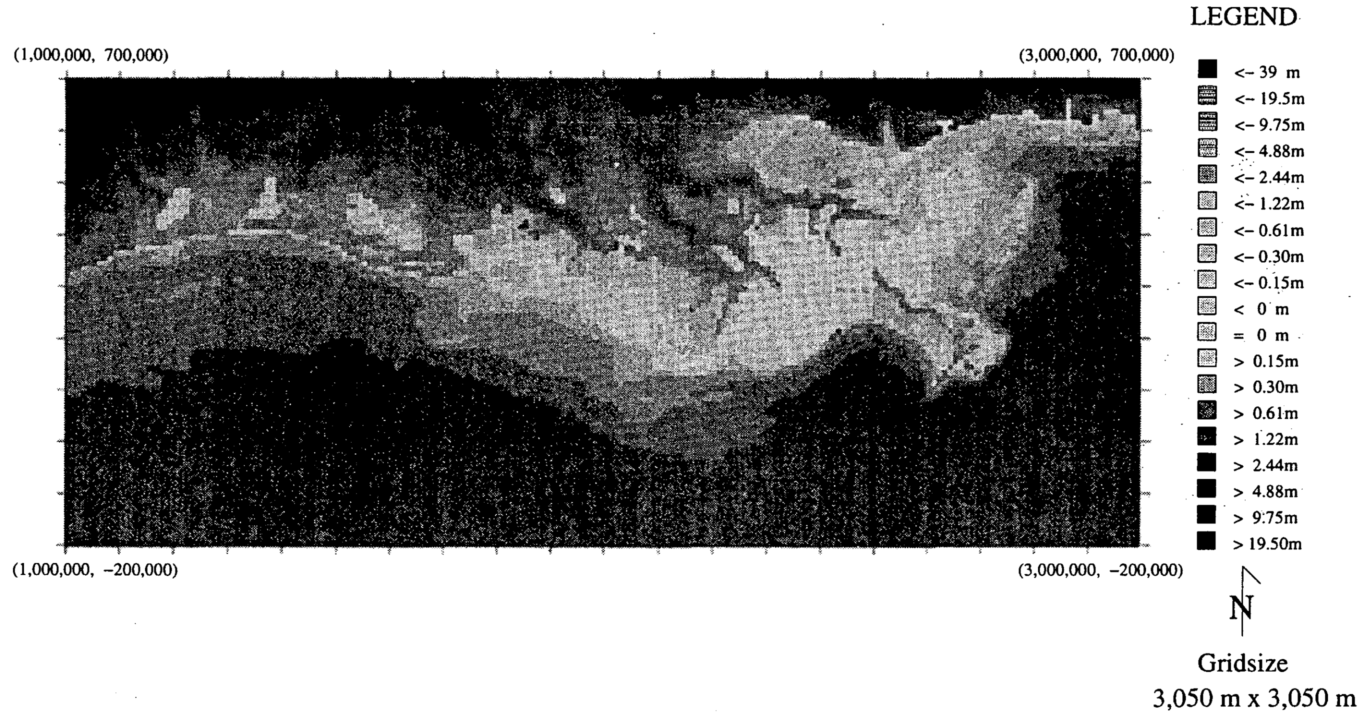

FIGURE 1 Offshore grid (depth and elevation).

extended into Texas along lines parallel to the Texas southern grid. The Louisiana and Texas grids were adjusted at the Texas and Louisiana border.

The number of river segments in the model was limited to 300. To represent accurately the effect of rivers on flooding, only rivers trending north-south were included in the river input files. Thus certain sections of the Gulf Intercoastal Waterway that were near the coast and trending an an east-west direction were not included. River data are shown in Figure 3. The barrier data input to the model were for the main roads and levees in the southern part of the coastal area of Louisiana. These barriers were placed at the boundaries of the grid cell nearest to their actual location. The barrier data base is shown in Figure 4.

Sensitivity Runs

Several surge simulations were computed to determine the sensitivity of the final water elevations to variations in the input parameters. The sensitivity runs were made using the offshore and inland grids and various combinations of hurricane parameters, barrier locations and elevations, and roughness parameters. The final offshore calibration run used the values of these parameters that produced the best agreement between the observed surge elevations and the predicted surge elevations at shoreline locations near the transfer grid cells.

The inland sensitivity runs involved varying several parameters: the position of the hurricane, the river depth, width, and roughnesses; the ridge elevations and locations; and the overland roughness and the tide level. In order of overall importance, the barrier elevation changes had the greatest effect on the still water elevations, followed by the overland roughness and the tide level. The sensitivity of the calibration computer runs to various values of the land Manning roughness were investigated in detail. Variable overland roughness was used in several simulations and did not produce a significant difference from constant roughness simulations.

Tide Calibration

The calibration of the inland grid was conducted using observed tide range and elevation data for various locations along the Louisiana coast and along waterways. Tide records from continuously recording tide gauges were obtained from the New Orleans District office of the U.S. Army Corps of Engineers. These tide gauges in many cases are at the same locations as gauges that have recorded hurricane surge elevations.

The tidal calibration for the western area of the state focused on the Calcasieu ship channel. Three tide gauges were used. The first gauge (No. 73650) was located at the mouth of the Calcasieu ship channel south of the city of Cameron. The second gauge (No. 73600) was located at Hackberry about 32 200 m north of Cameron. The third gauge (No. 73550) was south of Lake Charles about 72 450 m north of Cameron. The predicted elevations and time lags for a 4-day period were comparable to the observed elevations at Cameron and Hackberry. The predicted tidal elevation at Lake Charles was about .24 m lower than the observed level. This location is most affected by backwater in the Calcasieu Ship Channel and the operation of the Calcasieu Lock. The tidal ranges, based on the high tide, were well predicted at Cameron but were overestimated at Hackberry and Lake Charles.

The tidal calibration for the eastern part of the state focused on the Barataria Bay and Lake Pontchartrain basins. Tide gauge records for several locations in both basins were used. Tide gauge

FIGURE 2 Hurricane coastal flooding simulation.

locations used in the Barataria Basin were Grand Isle (No. 88410), Bayou Petit Caillou (No. 76305), Bayou Blue (No. 82301), Bayou Barataria at Lafitte (No. 82875), Bayou Barataria at Barataria (No. 82750), Houma (No. 76320), Bayou Des Allemands at Des Allemands (No. 82700), Bayou Chevrenul at Chegby (No. 82525), and Greenwood (No. 52880). In the Pontchartrain Basin, the tide gauges used were at Seabrook Bridge (No. 76060), Mississippi River gulf outlet at Shell Beach (No. 85800), Mandeville (No. 85575), West End (No. 85625), Mid-Lake (No. 85600), Regolets (No. 857001), and Irish Bayou (No. 85675). The tidal calibration simulations for a 4-day period showed good agreement in tidal range throughout both basins; however, the predicted tidal crest elevations were lower than the actual elevations. This occurred because there were mean water changes in the northern parts of the two basins that were related to wind tides and runoff outside of channels that were not accounted for in the model.

Hurricane Calibration

The hurricane calibration was conducted for five storms: Audrey, Carla, Betsy, Camille, and Andrew. These storms were selected to give a good geographic coverage of the state, even though several are dated. More recent storms, Juan, Gilbert, and Frederick, were reviewed, but because they produced little overland flooding in coastal Louisiana they were not useful. To calibrate the simulation model properly, the conditions that existed at the time of the hurricane would have to be reproduced. Some of the barriers in existence at present either were absent or had a reduced height in the past, river channels have deepened, several roadways have been raised, and marsh conditions have changed. The approach taken in the calibration effort was to use the present data base for the calibration simulations.

Hurricane Andrew is the most appropriate storm to be used for calibration because it occurred recently and reflects the current landscape conditions in the state. The storm data have been obtained from Rappaport (*2*) and Martin (E. Martin, Hurricane Andrew data for coastal Louisiana, personal communication, Feb. 1993). The central pressure reached a low of 937 millibars after crossing into the Gulf of Mexico. Calibration of the storm involved using 17 data points for which either gauge data or high water marks were available. The comparison of the observed and computed maximum surge elevations showed an average difference of −.15 m and a root mean square (RMS) difference of .46 m. Thus, the model slightly underpredicted the maximum surge elevations. This occurred near the point of landfall where the wind direction shifted 180 degrees as the storm passed.

Hurricane Audrey is the most appropriate storm for calibrating the chenier plain. The storm had a low central pressure and relatively constant pressure, radius, forward velocity, and direction. It produced water levels that met or exceeded the 100-year elevation. There were several gauge and overland water level observations available. Hurricane Carla was used as a calibration storm, although it did not produce significant ridge overtopping and therefore could only be used to calibrate river and waterway flooding. The calibration data points and geographic locations for Audrey were taken from previous studies (*3,4*). These reports list each observation, its location, and the source of the data. The gauge data stations are located on waterways and can be expected to be strongly influenced by waterway characteristics. This may not necessarily reflect overland water levels, even in proximity. The high water mark data are extensive and cover the full extent of Cameron Parish. Some of the data appear to be affected by both wave action and the exposure of the site. The calibration of the model was accomplished using the observed data to control the offshore and inland computations. The

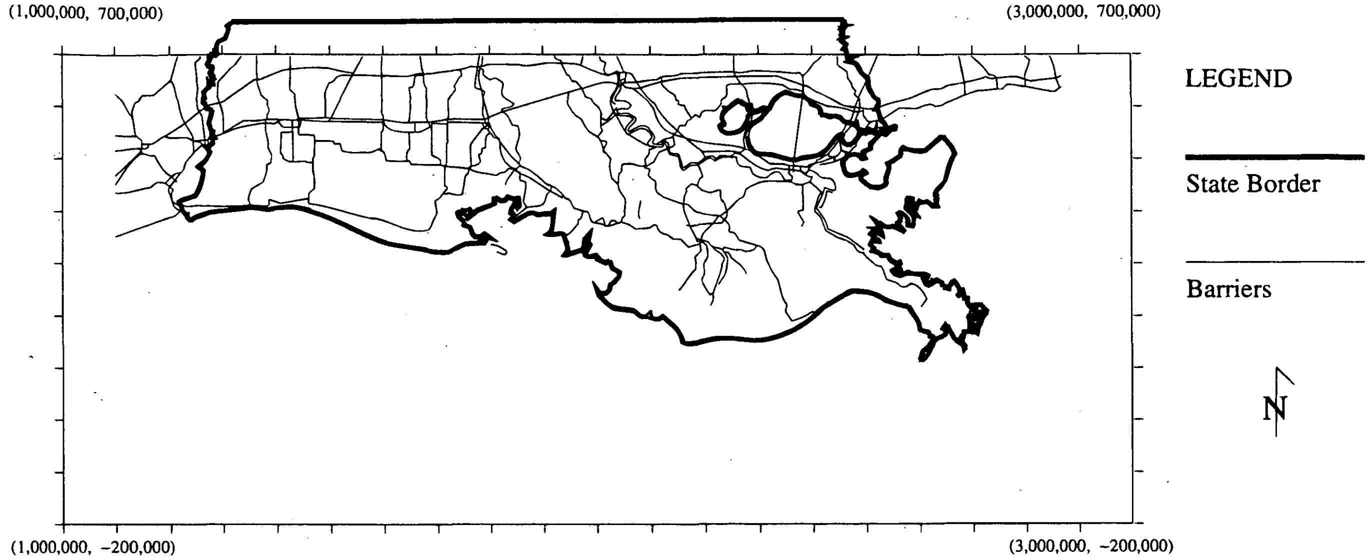

FIGURE 3 Barrier data.

surge elevations vary an average of about .31 m for a Manning's change from .033 to .039 m. The offshore calibration results showed a good agreement with the observed surge elevations at the grid points near the boundary transfer to the inland grid. The agreement between the observed and predicted surge elevations for the inland simulation was excellent. There was no average difference, and the RMS difference was .15 m. The agreement between observed and predicted surge elevations was very good at critical locations within the parish. At the Cameron Coast Guard station, the observed elevation was 3.69 m and the predicted was 3.90 m. The elevation differences at the Calcasieu Locks were also predicted. The predicted elevation was 2.32 m at the West Lock, compared with the 2.35 m observed, and the predicted elevation at the East Lock was 1.80 m, with an observed value of 1.68 m. The predicted elevation at the Hackberry gauge was 1.95 m, and the observed was 2.04 m. The still water elevation prediction at the head of Grand Lake was 1.46 m, and the observed value was 1.68 m. After being calibrated for Hurricane Audrey, the surge model was used without changes to the input topographic data.

JOINT PROBABILITY SIMULATIONS

The joint probability (JP) computer runs were conducted with control software developed particularly for this study. The FEMA surge program was rewritten to take input files consisting of the depth data, the hurricane data, and the input file. The multiple executions of the surge model were controlled by the batch file program. This batch file executes a Fortran program for each of the JP runs. The JP files for each run are identified by indicating each run parameter, so that P1R1V1D1.1 represents the first pressure, radius, velocity, direction, and track. The alongshore JP runs are designated as being a fourth direction, D4.

Set-Up of JP Runs

The JP runs were based on the hurricane discretization described in the previous section. The hurricane tracks were set up such that the track was constrained to pass through fixed points along the coastal line. The control points were along a latitude of 29.75 degrees and were separated by .50 degrees in longitude starting at a longitude of 89.00 degrees and extending westward to 95.0 degrees. The track separation was about 46 319 m, or about equal to the radius of a hurricane storm. The extreme eastward and westward limits were set based on producing a maximum shoreline surge elevation of less than 2.44 m. A total of 408 simulations was run. The output of the maximum elevations of the surge for the inland runs were saved as a maximum water elevation file, with extension MX, for example, P1R1V1D1.1MX.

Still Water Elevations

The final maximum still water exceedence probabilities for each of the inland grid cells were calculated by summing all the MX files, weighing each elevation with the appropriate probability. Thus, for each cell, the exceedence probability statistics were calculated. From these statistics, the water elevation for a fixed annual probability of rise in water level could be found. For an annual exceedence probability of .01, the elevation was interpolated from the exceedence statistics. The annual probability of .01 corresponds to an average return period of 100 years. The water elevations having annual exceedence probabilities of .002, .02, .04, and .1 were also interpolated for the average return periods of 500, 50, 25, and 10 years, respectively.

DISCUSSION OF RESULTS

Data Base

The data used in the study were obtained from a variety of sources having different dates. These data are critical to the accurate prediction of hurricane flood levels in coastal Louisiana. They were not all checked during the calibration phase of the study. Calibration is

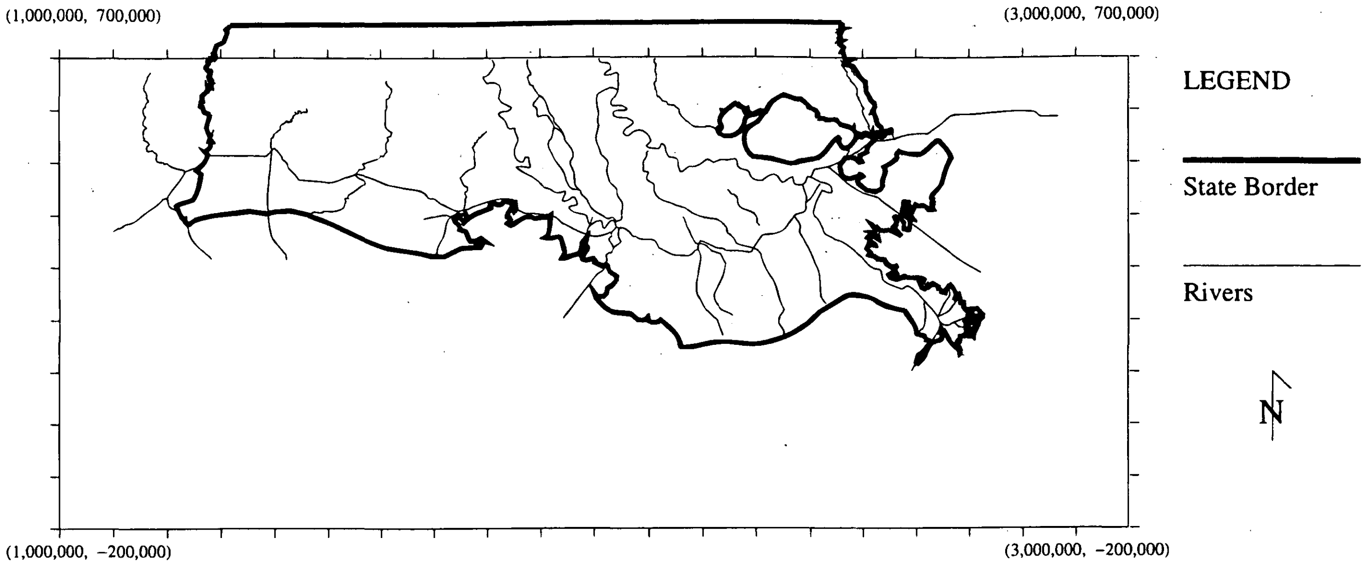

FIGURE 4 River data.

particularly sensitive to the hydraulic properties of the rivers and channels in the study area, both because the calibration data are taken in waterways and because all stages of flooding affect water elevations in waterways. The ground elevation and roughness properties of marsh areas of the study area could not be as well documented as barrier and river data, and there were not many observations of flooding in marsh areas. Thus, although the marsh areas make up most of the area in the study site and have an important effect on flooding, they are the least accurately determined components of the data base.

Model

The surge model used appears to be very well suited to the purposes of this study. It was capable of accommodating the significant landscape features of coastal Louisiana, and it performed well. The model has certain limitations that could have had a small effect on the computed flood elevations.

The model limits the number of grid cells, barriers, and rivers that can be included in the computations. This prevented some small subgrid scale features from being included in the modeling. Instabilities during simulations developed during the set up of the sensitivity runs that required reassignment of some land elevations near rivers. No difficulties were encountered in the calibration or production runs once these changes were made.

Use of Model

The setup of the grids based on the Lambert coordinates was convenient and allowed the grids to be referenced on virtually any topographic maps. The NOS charts, however, do not include Lambert tick marks, so the use of these charts required manual plotting of Lambert coordinates. The grid sizes used appear to be adequate to the purpose of simulating extreme hurricane surges. For less severe storms, water movement would be influenced by smaller channels than could be represented at the 3048-m resolution.

CONCLUSIONS AND RECOMMENDATIONS

Based on the data base and methodology used in this study the following conclusions can be made:

- The hurricane flood elevations in Louisiana indicate that flooding of transportation facilities in coastal Louisiana will be severe enough to require incorporation into design of new facilities.
- The landscape changes taking place in coastal Louisiana are of sufficient magnitude to modify the threat of hurricane flooding to transportation facilities in this area.

It is recommended that the predicted flood elevation statistics be periodically updated by recomputing the flood statistics using new data as they become available. The new data should include new landscape features, such as highways, levees, and channels. The model should incorporate any of the major changes in the landscape of Louisiana's coastal zone that are being planned by the Coastal Restoration Division of the Department of Natural Resources that will have an effect on hurricane flood elevations. This update would involve preparing a new users manual, which would need to be distributed to the appropriate LaDOTD offices.

It is also recommended that the acquisition of new data for the marsh areas of the coast be initiated and that the data be incorporated into the data base for the model. Specifically, this would include obtaining marsh water level and ground level data referenced to a suitable datum, such as the latest NGVD. Data could routinely be obtained from professional surveyors who in the course of their work would survey marsh areas. Also, several federal, state, and local governmental agencies are involved in monitoring water levels in marsh areas. In particular, the Coastal Restoration Division of the Department of Natural Resources is supplying several marsh sites in coastal Louisiana with tide gauges. The data from these sources would be useful in the future for updating the hurricane flood elevation statistics.

REFERENCES

1. Ho, F. P., J. C. Su, K. L. Hanevich, R. J. Smith, and F. Richards. *Hurricane Climatology for the Atlantic and Gulf Coasts of the United States.* National Oceanic and Atmospheric Administration, Water Management Division, Office of Hydrology, National Weather Service, July 3, 1986.
2. Rappaport, E. *Preliminary Report Hurricane Andrew.* National Hurricane Center, Miami, Fla., March 2, 1993.
3. *Hurricane Audrey—27 June 1957.* U.S. Army Corps of Engineers, Memorandum Report, New Orleans District, Sept. 30, 1960.
4. Harris, D. L. *Characteristics of the Hurricane Storm Surge.* Technical Paper 48, U.S. Department of Commerce, 1963.