REVIEW OF THE APPLICATION OF THE NUMERICAL MODEL "ADCIRC" FOR STORM SURGE PREDICTIONS IN THE NEW ORLEANS, LA VICINITY

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1.0 Introduction

1.1 Background

This report presents the results of a four year effort to improve and assess the capability of the long wave numerical model "ADvanced CIRCulation" (ADCIRC) to predict storm surges in that part of Louisiana and Mississippi south of Baton Rouge with a specific focus on storm surges in Lake Pontchartrain, levees surrounding New Orleans, and waterways within its vicinity. This effort was sponsored by the New Orleans District of the U. S. Army Corps of Engineers (USACE). The ADCIRC modeling was carried out by Professors Joannes J. Westerink of Notre Dame University and Richard A. Luettich , Jr. of the University of North Carolina at Chapel Hill, the two developers of the model. Logistics, information resources and guidance were provided by Staff of the New Orleans District of USACE, notably Mr. Jay Combe, Dr. Harley Winer, Dr. Hasan Pourtaheri (now with the Wilmington District of the Corps), Mr. Vann Stutts, Mr. Burnell Thibodeaux and many others. Technical oversight was provided by the Authors of this report who were appointed by the Corps to serve on this effort as a Technical Review Committee (Hereinafter, TRC).

The motivation for this effort is the question of whether the Lake Pontchartrain and other levees are of adequate elevation to protect the City of New Orleans and vicinity from storm surges associated with severe hurricanes, and if not, what changes are required. To address this question, the New Orleans District decided in Spring of 2000 to carry out investigations of the capabilities of the state-of-the-art numerical long wave model ADCIRC (about version 40) by the developers of this model with the TRC serving as an independent advisory and evaluation committee. The charge to TRC encompassed only a portion of the overall design chain required to determine potential storm surge elevations and arrive at a decision as to whether or not the Lake Pontchartrain levees and other levees are of sufficient elevation. The following paragraphs discuss the overall components leading to such a design determination and delineate the elements on which recommendations by the TRC were requested.

The overall determination of whether the Lake Pontchartrian and other levees are of adequate elevation depends on a number of factors, including: (1) Design storm surge calculations (2) Hurricane statistics, (3) Wave runup, (4) Levee crest elevations relative to an appropriate datum including effects of regional and local subsidence, and (5) Possible non-technical issues. The responsibilities of the TRC are limited further to a subset of the issues relating to the design surge calculations as discussed below.

The overall components which influence the design surge calculations include: (1) Accuracy and uncertainty in joint surge and tide calculations for a given hurricane structure, intensity, path, and time of landfall, (2) Accuracy and uncertainty of the model used for representing the wind and pressure structure, (3) Statistics of the parameters governing the hurricane model, (4) Method of accounting for the hurricane statistics [Joint Probability Method (JPM) or Empirical Simulation Technique (EST)]. The TRC responsibility is only in the first item although we do address Item 2 and include discussion of some of the other items. As will be evident, developing an assessment of the accuracy of the ADCIRC model in predicting storm surges involves both evaluation of computation results and judgment.

To the best of our knowledge, this comprehensive effort to develop/calibrate and evaluate a numerical storm surge model is unprecedented in its scope and level of effort.

1.2 The Process

In general, the process included refinement/calibration/development of ADCIRC through further consideration of the governing physics and comparison with data from two hurricanes, Betsy (1965) and Andrew (1992). This phase was conducted using the Planetary Boundary Layer (PBL) model for wind and barometric pressure forcing. Following this phase, the model was fixed and production runs were conducted with the hurricanes listed in Table 1.1. The production runs also included wind and barometric pressure forcing of Hurricanes Betsy, Isidore and Lili based on the NOAA Hurricane Research Division (HRD) methodology for producing gridded wind and barometric fields from available data for the particular hurricane.

Table 1.1
Summary of Hurricanes Included in Effort, Their Roles
(Calibration and/or Production Runs) and Characteristics of Wind Fields

Hurricane	Calibration (C) and/or Production (P)	Wind Fields Employed
Unnamed (1947)	(P)	PBL
Audrey (1957)	(P)	PBL
Hilda (1964)	(P)	PBL
Betsy (1965)	(C) & (P)	PBL & HRD
Camille (1969)	(P)	PBL
Edith (1971)	(P)	PBL
Carmen (1974)	(P)	PBL
Andrew (1992)	(C) & (P)	PBL
Georges (1998)	(P)	PBL
Isidore (2002)	(P)	PBL & HRD
Lili (2002)	(P)	PBL & HRD

315,000
50 K
50 meter

The Modelers produced hydrographs for locations of standard Corps of Engineers and other agencies gages which included measured and calculated surge histories. These were inspected to identify significant peak surges which were then subjected to statistical analyses to evaluate the ADCIRC model using PBL and HRD forcing and to establish a basis for application of ADCIRC predictions for design using PBL forcing.

1.3 A Look at the Future

Future modeling improvements will undoubtedly be made to the various elements (wind fields, wind stress coefficients, wave setup, etc) on which the surge predictions depend. Additionally, with time, the historical hurricane statistical data base will be enhanced and subsidence issues will be clarified/updated. At some stage in the future, it would be appropriate to repeat the effort here including the follow on design calculations based on model and data base improvements.

1.4 Bibliography

A bibliography comprising papers and reports related to storm surges is presented as Section 8 of this report. Although only a small number of these documents are cited directly in this present report, the greater number is included for general background purposes.

2.0 Capabilities of and Improvements to ADCIRC

2.1 Background

When this four year project was initiated, ADCIRC included the capability of wetting and drying as the water level rose to exceed or fell to be less than the elevations of the adjacent topography. Additionally, at that stage the model had been developed over a number of years, was documented extensively in the peer reviewed literature as the references to this report will demonstrate and had undergone substantial testing. However, the calibration/development phase, which involved further consideration of the governing physics and comparisons with the measured storm surges of Hurricanes Betsy (1965) and Andrew (1992) established that a number of further modifications could result in greater realism in the model predictions.

This section documents the modifications to ADCIRC that were carried out during the calibration phase and attempts to provide, where possible, the motivation for the modifications and discussion of improvements achieved.

2.2 Modifications to ADCIRC During Calibration/Refinement Phase

The various modifications that were carried out during the design phase are presented in Table 2.1 and are discussed further in the following sections.

2.2.1 Slip Boundary Condition

The version of ADCIRC available at the commencement of this project included a "no-slip" boundary condition at the model lateral boundaries. It was found, in cases where the flow being represented was in narrow waterways, that the effect of the no-slip lateral boundary condition tended to overly retard the overall flow. Thus, a slip lateral boundary condition was introduced which resulted in improved agreement between measured and calculated flows as well as producing a more realistic surface slope.

2.2.2 Upstream Radiation Boundary Condition

Comparison of measured and calculated storm surges in the Mississippi River during Hurricane Betsy established that in the lower reaches, the surges were quite similar; however with increasing upriver distances, the shape of the surges differed with the calculated surges characterized by a double peak in some cases. Further examination of these calculated surges established that this effect was due to a reflected wave from the upstream model boundary. Several approaches were investigated with the final modification being the incorporation of a radiation condition at the upstream boundary of the ADCIRC model which allowed the upstream propagating surge to continue upstream with relatively small reflection. This significantly suppressed the reflection of the surge reaching the simulated location of Baton Rouge and produced much more realistic results at the downstream locations in the Mississippi River simulations with Hurricane Betsy and Andrew forcing. The effectiveness of this boundary condition was verified further by comparison with results from a model domain which extended a great distance upriver.

Table 2.1

Summary of Various Modifications Made to ADCIRC During the Calibration Phase

Modification	Motivation for Modification	Description of Modification
Slip Boundary Condition	Initial no-slip lateral boundary condition tended to overly restrain flow	Apply no-slip boundary condition to lateral boundaries
Upstream Radiation Boundary Condition	Initial reflection boundary condition at upstream Mississippi River resulted in surges that differed from measured farther up river	Radiation boundary condition applied at upstream ADCIRC boundary to allow surge to continue upstream through boundary
Wind Stress Relationship	Recognition that design winds will exceed those included in study calibration phase and the large ranges of stress relationships	Adopted the Garratt wind stress relationship with no limitation of the maximum stress coefficient
Land Roughness Coefficients	Presence of large expanses of open water, much of which is vegetated and excessive predicted blowdowns in Lake Pontchartrain.	Development of a look-up table for incorporation of local roughness effects.
Under Canopy Drag	Recognition of the large reductions in stress applied to water surface for the case of vegetation protruding through the water surface	Set under canopy wind stresses to zero

2.2.3 Wind Stress Relationships

A significant number of wind stress relationships have been proposed and are available in the peer reviewed literature. Of particular interest to this effort are the wind stress coefficients at high wind speeds. Recent results obtained from GPS drop sondes in hurricanes (Powell, et al, 2003) suggest that after an initial increase with wind speed to hurricane force, the drag coefficient levels off or even decreases with further wind speed increase. However, these results are applicable only over the open ocean and the authors caution their use near the coast where other studies in non-hurricane conditions (Anctil and Donelan, 1996) suggest that breaking and shoaling waves may contribute to larger sea surface roughness and accompanying increase in drag coefficients. Based on considerable sensitivity testing and evaluation, a decision was made for purposes of this study, to use the Garratt wind stress coefficient with no limiting stress coefficient for high wind speeds.

2.2.4 Land Roughness Coefficients

Land roughness can be due to vegetation, buildings, levees, etc and, through increasing the boundary layer thickness, or through direct transfer to the roughness elements rather than to the water, the wind stress applied to the water surface and resulting water surface slopes can be reduced considerably. This issue also encompasses wind direction since wind directed from a heavily vegetated area will require a transition distance before reestablishment of the normal stress transfer mechanisms.

During the development phase, it was recognized that the winds over land and especially, the offshore flow regions were depicting open ocean flow conditions which had the effect of much larger than observed draw-downs to the west of New Orleans during Hurricane Betsy. It was also recognized that some of the coastal inundation areas comprised forest which would impact the drag coefficient. These issues were addressed by applying a method in use by HRD to convert marine flow to that over open terrain. The required Land Use/Land Cover (LULC) data were obtained by a combination of available information supplemented by efforts of New Orleans District personnel to improve the characterization of the LULC data. This information formed the basis of a look up table which allowed the surface roughness to be characterized by wind direction to 20 km upwind from each affected grid point.

2.2.5 Under Canopy Drag

In forested and heavily vegetated areas that might be flooded, it is recognized that the winds are significantly reduced within such regions and thus the wind stress on the water beneath such a canopy is likewise significantly reduced. Reid and Whitaker (1976) give formulas for the wind reduction factor in terms of the typical dimensions of the vegetation and their number per unit horizontal area. Based on a number of sensitivity tests and lacking detailed information for the vegetated areas in the study area for this project, the production runs set the wind stress equal to zero in vegetated areas.

3.0 Uncertainties in the Process

3.1 General

There are uncertainties associated with the process of evaluating the skill of ADCIRC in both the calibration and production runs and in the predictions on which future decisions regarding levee elevation will be based. Some of the uncertainties in the calibration and production runs should be reflected in the later design predictions and others should not. This section addresses these issues and discusses the appropriateness for inclusion of the various sources in the later calculations on which the current levee elevations will be evaluated and, where necessary, design modifications based.

3.2 Uncertainty Sources

The possible sources of identified uncertainties are presented in Table 3.1. Also indicated is the manner in which these sources contribute and whether they should be considered as contributing to the design process. Each of these sources is discussed below.

3.2.1 Wind and Pressure Fields

To provide a basis for estimating the portion of error associated with the PBL winds and barometric pressure fields used to force the long wave model ADCIRC, the Corps requested that NOAA's Hurricane Research Division (HRD) conduct a reconstruction of the Hurricane Betsy wind field and to provide additional meteorological information. Reconstruction of the Hurricane Lili and Isidore wind fields were added after the 2002 hurricane season. These reconstructions are based on input from all available sources including anemometers, barometers, research aircraft and satellites and the data contributing to the reconstruction are screened thoroughly for quality. The methodology has been applied to analyze the landfall characteristics of several major hurricanes as documented in peer reviewed literature (Powell, et. al., 1991, Powell and Houston, 1996, 1998, Powell, et. al. 1998). The resulting reconstructed wind fields depict the wind direction and speed over a fine resolution Cartesian grid, and depict the radius of maximum wind. The radius of maximum wind and the minimum sea-level pressure in the eye of the storm were specified every 3 hours for each storm track. The current accuracy to which wind centers of tropical cyclones may be located is approximately 1 km. It should be noted that the wind, pressure, and geometric eye centers of tropical cyclones do not always coincide and may vary be several km. In addition, hurricanes in the process of transforming into extratropical systems will frequently have considerable tilt in the wind centers of tens of km between the surface and the height where most reconnaissance is flown (3 km). The HRD representations should provide the better representations for forcing the long wave model. Uncertainties in the Hurricane Betsy wind field are considered greater than those for the Lili and Isidore fields since Betsy predated the era of high quality aircraft data communications.

Table 3.1

Sources of Uncertainties in the Overall Process and Their Significances

Uncertainty Source	Uncertainty Origin/ Explanation	Should be an Uncertainty Source in The Design Process?	Comment
Wind and Pressure Fields, Actual vs Model	Variability of Actual Wind Fields	Yes	Inherent in Variability Present in Production Runs
Any Inaccuracies in ADCIRC Model	Complexities in Hydrodynamics	Yes	Inherent in Variability Present in Production Runs
Inaccuracies in Representing Characteristics of Natural System	Complexity of Natural System: Topography, Vegetation, Roughness, etc	Yes	Inherent in Variability Present in Production Runs
Inaccuracies in Hurricane Tracks	Tracks of Production Runs May Contain Inaccuracies	No, if the Historical Hurricane Data Base is Accurate	Inherent in Variability Present in Production Runs
Wind Stress Coefficients	Canopy Effects, Coefficients at High Wind Speeds, etc	Yes	Inherent in Variability Present in Production Runs
Historical Hurricane Data Base	Limited Number of Severe Strength Storms	Yes	This Will Be a Factor in the Later Design Calculations
Subsidence Effects			Not Inherent in Variability Present in Production Runs. Will Be a Factor in the Later Design Calculations
Steric Effects	Inherent Variability in Mean Seasonal Water Level Fluctuations	Yes	Variability Not Present in Production Runs
Wave Setup	Not in ADCIRC	Not if Incorporated in ADCIRC	Explicit Incorporation Would Reduce Uncertainty
JPM or EST	Method of Representing Storm Statistics	Yes	Consideration Required in Design Calculations

Comparisons of the PBL and HRD wind fields have identified several significant and systematic differences between these forcings. In particular, the PBL model has a tendency to predict too broad a region of strong winds in most storms. Additionally, after landfall, the PBL model predicts too much broadening of the wind field. This appears to be a result of a built in dependency in the PBL model of the radius to maximum winds and the central pressure deficit. Because the PBL model will be used for levee elevation evaluation and design, these issues should be addressed in future refinements of the PBL model.

Obviously, the HRD wind fields will not be available for design purposes although it is possible that in the future some of the systematic characteristic differences found between the HRD and the PBL wind fields (as noted above) could be incorporated in the design phase to provide an improved model. At this stage, we consider that the benefits of the HRD fields will not be available for design purposes. Rather, these benefits will be developed and applied in the future and will provide improved meteorological forcing to ADCIRC and thus contribute to reducing the uncertainties in ADCIRC predictions, given a particular meteorological forcing. It will be shown later that the HRD wind fields generally (2 of 3 areas) produced better agreement than the PBL winds with the measured surges allowing for a constant factor difference which is interpreted as due to calibration based on PBL rather than HRD wind fields.

As noted, the PBL model (or a future improved model) will be used in the later design calculations. Although some questions remain regarding the appropriateness of the tracks and hurricane radii used in the production runs, if those tracks and radii were appropriate, the statistical results of the comparisons of the production run surges and the measured surges based on the ADCIRC model will incorporate the proper uncertainty to be included in the design calculations.

3.2.2 Inaccuracies in the ADCIRC Model

Section 2 of this report detailed a number of substantial improvements that were made to the ADCIRC model during this four year effort. Undoubtedly other improvements will follow including some means of incorporating wave setup (discussed in more detail later) in the storm surge predictions. Any present inaccuracies in the ADCIRC model would be reflected in the statistics of the comparisons of the predicted and measured peak surges.

3.2.3 Inaccuracies in Characterizing Natural System

Efforts were made to characterize the natural system faithfully including the vegetation characteristics, relative ground levels at the times of the historical storms included in this effort, bathymetry, etc. However, future efforts may establish further improved characterizations of the natural system. Regardless, predictions of surges due to future hurricanes should include a conscientious effort to consider a range of relative ground elevations consistent with known rates of subsidence and ranges of times of storm occurrence. If relative sea level continues to rise at present rates and any corrective actions are relatively ineffective, future conditions will include more open water and less vegetation. Regardless, any inaccuracies in characterization of the present and past systems should be represented appropriately in the statistics of the comparison of the predicted and measured peak surges.

3.2.4 Inaccuracies in Hurricane Tracks

Some uncertainty remains as to whether some of the production runs were conducted with the best hurricane track descriptions. Any inaccuracies in the hurricane track should have the effect of increasing the differences between the predicted and measured peak surges. Thus, this should result in a recommended uncertainty to be considered in design which is greater than the actual uncertainty, ie the design calculations would produce overly conservative results through incorporation of uncertainties which are too large.

3.2.5 Wind Stress Coefficients

The Garratt wind stress coefficients were incorporated into the calculations. There are relatively few measurements at the higher severe storm associated wind speeds to be considered in design and this is an area of active research. As discussed in Section 2.23, recent investigations suggest that wind stress coefficients may level off or decrease at very high wind speeds. If the wind stress coefficients were constant with increasing wind speed, an inappropriate stress coefficient would be offset through calibration (probably by adjusting the wind stress coefficient). However, for stress coefficients which vary with wind speed, such an adjustment is only appropriate for the wind speeds represented in the calibration and the surges in rare hurricanes could tend to be overestimated. For purposes here, the Garratt wind stress relationship was adopted without consideration of a limiting stress coefficients at high wind speeds.

3.2.6 Steric Effects

The steric contributions to mean water level are a result of the seasonally reduced density of the water due to thermal and fresh water effects. Thus, the steric contribution can be characterized by a monthly average and a statistical distribution about that average. As will be evident later, uncertainties in steric effects were avoided in the evaluation data base which compared the differences between the peak surges (measured and computed) and their respective mean water levels immediately prior to the hurricane induced water levels. In design it will be necessary to include both the mean steric contribution (appropriate for the hurricane season months) and an approximation of the contribution due to the statistical uncertainty in steric water levels.

3.2.7 Historical Hurricane Data Base

The historical hurricane data base statistics will be used later in the surge calculations to determine whether or not levee elevations are adequate, and if not, the appropriate additional elevations. Although uncertainties in this data base do not affect the results of the present study, these uncertainties will contribute to assessment of the return periods of the peak surges determined in the design stage.

3.2.8 Subsidence

Past and future subsidence and eustatic sea level rise are of relevance to the later design stage. Subsidence includes both regional effects and local effects due to the weight of the levees. Considering the high relative sea level rise rates in the general Mississippi River delta region (order of 100 cm per century) and somewhat lower rates in the vicinity of New Orleans, current eustatic (world wide average) sea level rise rates of approximately 12 cm per century are relatively small. Any effects of subsidence are not incorporated into the uncertainties determined herein because we base the evaluation on the peak surge deviations from the pre hurricane effect water levels and an attempt was made to base the relative sea level in the calculations on the relative water levels at the time of hurricane occurrence. However, appropriate incorporation of subsidence effects (regional and local, present and future) will be critical to the assessment of the adequacy of present levee elevations and the design for future levee elevations.

3.2.9 Wave Setup

Wave setup is the surge component resulting from the transfer of wave related momentum to the water column as a result of wave dissipation. The effect of this transfer is in the form of a force on the water column much like that due to a wind stress although the force due to wave momentum transfer is distributed throughout the vertical dimension of the water column rather than at the surface as for wind stress. Although the basic physics of wave related setup are well understood, to date explicit incorporation into ADCIRC has been precluded by the complexities associated with this incorporation. Wave setup was not included explicitly in the calculated results presented herein.

3.2.10 JPM or EST

The Joint Probability Method (JPM) and the Empirical Simulation Technique (EST) are the two general approaches to incorporating the historical hurricane characteristics into the simulation of a series of storms and the quantification of the return periods of the resulting storm surges. This is not an issue in the present effort and questions regarding which of these two methods is more applicable must be addressed during the design phase. Since these two methods rely on the same historical hurricane data base, properly applied, they should yield the same approximate results. Considering the significance of the overall question of adequacy of levee elevations, at this stage, it appears reasonable to apply both methods in the design phase.

8.0 Bibliography

8.1 Introduction

The following bibliography contains reports, journal papers, and other documents arranged by categories. Within each category, the entries are arranged chronologically with oldest documents first and most recent appearing last.

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8.2.1 Prior Skill Assessments of Storm Surge Models

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