OSCILLATIONS OF SEMI-ENCLOSED WATER BODY INDUCED BY HURRICANES

by

Yuan-Hung Paul Tan

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Abstract

A numerical study is conducted to simulate the oscillations (storm surges) of semi-enclosed water body induced by hurricanes. For application using the numerical model developed in the present study, Lake Pontchartrain (located in southeastern Louisiana) is chosen as the semi-enclosed water body and Hurricane Katrina (the costliest hurricane in the history of the United States) is chosen as the hurricane. There are three (3) reasons to choose Lake Pontcharrain and Hurricane Katrina: 1. Storm surge built up in Lake Pontchartrain during Hurricane Katrina, 2. Wind drove water into Lake Pontchartrain as Hurricane Katrina approached from the Gulf of Mexico, and 3. The extensive field data, gathered by the Interagency Performance Evaluation Task Force (IPET), is available to provide the needed comparison of numerical result and prototype data on the oscillations at Lake Pontchartrain induced by Hurricane Katrina.

The depth-average, non-linear shallow-water equations (NLSW) are use as the governing equations. The finite-volume method (FVM) is employed to solve the governing shallow-water equations. In order to validate the present model, the hydrographs due to Hurricane Katrina obtained from the present model are compared with the field data reported by IPET at eight (8) sites along the shores and the center of Lake Pontchartrain. These eight (8) sites are: the 17th street Canal, the Orleans Avenue Canal, the London

Avenue Canal, the Inner Harbor Navigation Canal (IHNC)-Lakefront Airport, Midlake, Bayou Labranch, Pass Manchac, and Little Irish Bayou.

The time at which the maximum water surface elevation (WSE) occurs as predicted by the present model is almost identical to the time at which the maximum water level is observed at the 17th Street Canal, the Orleans Avenue Canal, the London Avenue Canal, and the IHNC-Lakefront Airport sites. Furthermore, the present model correctly predicts the general trend of the water level when the hydrographs due to Hurricane Katrina are compared with the observed hydrographs at the 17th Street Canal, the Orleans Avenue Canal, the London Avenue Canal, the IHNC-Lakefront Airport, and the Midlake sites. However, the present model only reasonably predicts the general trend of the water level when the hydrographs due to Hurricane Katrina are compared with the observed hydrographs at the Bayou La Branche (named Bayou Labranch by IPET), the Pass Manchac, and the Little Irish Bayou sites.

The present model is further applied to investigate the oscillations at Lake Pontchartrain induced by four (4) synthetic hurricanes within the time-span of 00:00 UTC August 29, 2005 to 00:00 UTC August 30, 2005: Case 1. Hurricane Katrina tracks on its original route, Case 2. Hurricane Katrina tracks 36 km west of its original route, Case 3. Hurricane Katrina tracks 72 km west of its original route, and Case 4. Hurricane Katrina tracks on its original route with forward speeds reduced by 16% ~ 45% (or altered from 15 km/h ~ 36 km/h to 15 km/h ~ 22 km/h). These are done to assess the impact of hurricanes under different risk conditions. It is found that much more severe catastrophes in metro New Orleans and neighboring parishes can be expected under the scenarios of: Case 2. Hurricane Katrina passes through the east part of New Orleans, Louisiana and both the east and central parts of Lake Pontchartrain and Case 4. Hurricane Katrina passes through the regions nearby the east shore of Lake Pontchartrain with reduced forward speeds.

Chapter 1: Introduction

1.1 Background

Higher-than-normal water levels and wave conditions observed during hurricanes are primarily forced by the wind associated with hurricanes. Wind exerts a shear stress on the water surface that pushes the water. Wind is very effective in developing the storm surge in shallow water.

The process that wind changes the water level is called storm surge generation. Storm surge (oscillation) defined here is the abnormally “Still” high water level induced by the hurricane. The word “Still” used here is to distinguish the slower rise and fall of the water surface due to the storm surge/tide that occurs over time scales of hours from the changes in water surface that occur at much higher frequencies associated with the continuous up and down water surface motion due to wave motion which occurs over time scales of seconds and tens of seconds.

The storm surge generated by the hurricane is related to the surface shear stress. The shear stress generated by the wind associated with hurricane is related to the wind speed with a highly non-linear relationship. Broad, shallow continental shelf regions are susceptible for developing storm surge. As wind pushes water, storm surge moves and accumulates as it encounters a coastal land mass or other obstruction. The key topographic controls along the U.S. coast, such as indentations, irregularities, and pockets, are particularly susceptible to catching water pushed toward and into these geographic features by the wind associated with hurricanes.

The Mississippi River delta is holding a coastal land characteristic that acts to catch water being pushed toward it along the Mississippi and Alabama continental shelves. Hurricanes in the northern Gulf of Mexico tend to generate winds that blow from the east in the northern Gulf since they are rotating in the counterclockwise direction. These east winds push water toward southern Louisiana, approaching the Mississippi River delta.

The city of New Orleans in the State of Louisiana is located in the low-lying Mississippi River delta, and major portions of the city lie near or below sea level. The greatest natural threat presented to residents and properties in New Orleans area has been hurricane-induced storm surges, waves, and rainfall since the founding of the city in 1718. A comprehensive hurricane protection plan was not initiated until Hurricane Betsy struck the city in 1965, killing 75 people and causing substantial damage and loss of property. Over time, three (3) hurricane protection projects have been planned and partially implemented in New Orleans and the Southeast Louisiana region: Lake Pontchartrain and Vicinity, the West Bank project, and the New Orleans to Venice project.

Lake Pontchartrain is a brackish lake located in southeastern Louisiana. It is the second largest salt-water lake in the United States (after the Great Salt Lake in Utah) and the largest lake in Louisiana. It is roughly oval in shape, about 40 miles (64 km) wide and 24 miles (39 km) from south to north. It covers an area of 630 square miles (1630 square km) with an average depth of 12 to 14 feet (about 4 meters). The south shore forms the northern boundary of the city of New Orleans. Storm surge can build up in Lake Pontchartrain during hurricanes. Wind drives water into the lake from the Gulf of Mexico as a hurricane approaches from the south, and water can spill into New Orleans from the lake.

In order to protect areas around Lake Pontchartrain from flooding caused by a storm surge or rainfall associated with a hurricane that would be roughly classified as a fast-moving 'Category 3" hurricane, the Lake Pontchartrain and Vicinity hurricane protection project was authorized under the Flood Control Act of 1965 by Congress. As of May 2005, 125 miles of levees, major flood walls, flood-proofed bridges, and mitigation dike on the west shore of Lake Pontchartrain were built under this project and the estimated completion date for the entire project was 2015.

A hurricane is a remarkably well-organized, huge convection system that pumps great amounts of warm, moist air into high levels of the atmosphere at very rapid rates. Warm, moist air ascends sharply into the ring between 20 and 80 km of the center. Because of condensation, the temperature above about 1000 m within this ring increases fiercely toward the “eye” of the hurricane; consequently, the eye is significantly warmer than the exterior of the hurricane. As the air within this ring rises, new air flows in toward the center from hundreds of kilometers away. If the air starts out with even a slight rotary motion, it will spin faster and faster as it nears the center. A graphic illustration of these physical mechanisms is shown on Figure 1.1.

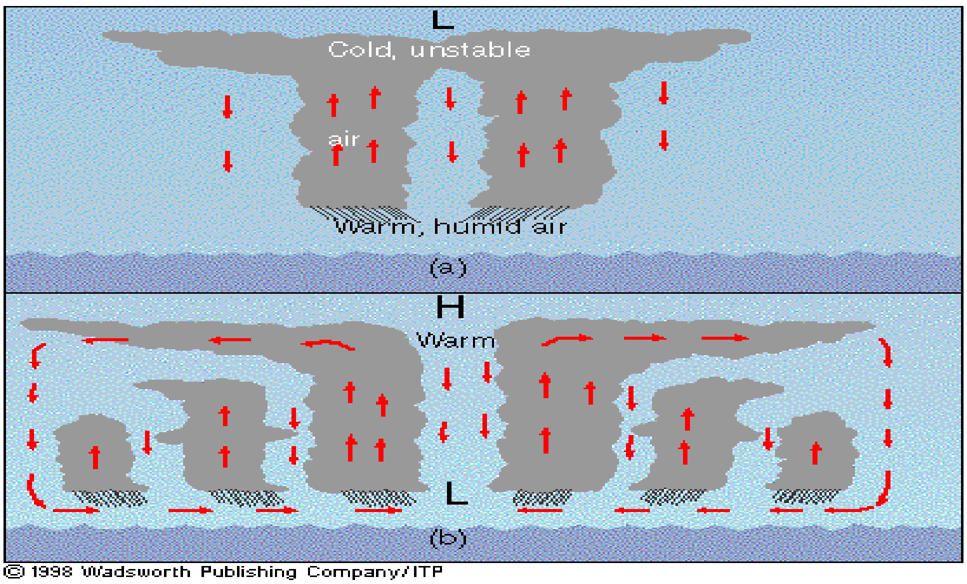

Figure 1.1 2-D View of Hurricane (Survey of Meteorology at Lyndon State College)

The circulation of a well-developed hurricane extends vertically to 14 or 15 km, almost to the level of the tropopause, although the intensity of the cyclonic circulation decreases with height. In the lowest 3 km, a pronounced trend of motion points toward the center of the hurricane, causing convergence of the air and the ascending motion that leads to cloud formation. The air flows with an outward fashion above about 7.5 km, and reaching a maximum rate at 12 km. Frequently, the air flow changes direction drastically in the uppermost layer as it moves outward from the center, and even acquires an anticyclonic rotation some 130 to 160 km from the center. These phenomenal descriptions are depicted in Figure 1.2.

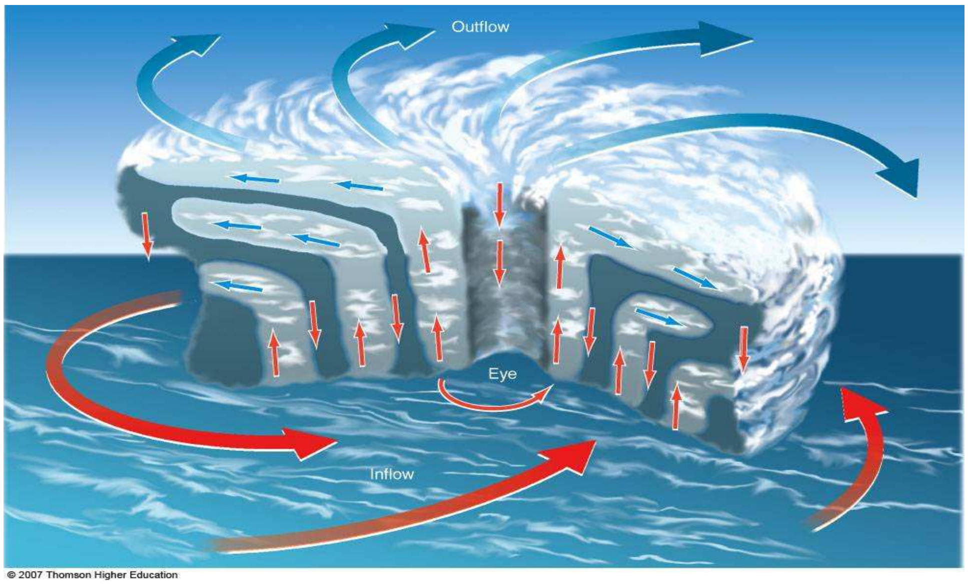

Figure 1.2 3-D View of Hurricane (Survey of Meteorology at Lyndon State College)

Hurricane Katrina was formed over the Bahamas on August 23, 2005, and crossed southern Florida as a moderate Category 1 hurricane. It then strengthened rapidly in the Gulf of Mexico and became one of the strongest hurricanes on record while at sea. The hurricane weakened before making its second and third landfalls as a Category 3 storm on the morning of August 29 in southern Louisiana and at the Louisiana/Mississippi state line, respectively. Hurricane Katrina was the costliest and one of the five deadliest hurricanes in the history of the United States. It was the sixth-strongest Atlantic hurricane ever recorded and the third-strongest hurricane on record that made landfall in the United States.

During Hurricane Katrina, the storm surge generated by wind exceeds 15 feet (approximately 4.6 meter) in places along the southern Louisiana coast and exceeds 20 feet (approximately 6.1 meter) in places along the Mississippi coast. It devastated the Mississippi cities of Waveland, Bay St. Louis, Pass Christian, Long Beach, Gulfport, Biloxi, Ocean Springs, and Pascagoula along the Gulf Coast. In Louisiana, the federal flood protection system in New Orleans failed in more than 50 places. Nearly every levee in metro New Orleans breached as Hurricane Katrina passed east of the city, subsequently flooding 80% of the city and many areas of neighboring parishes for weeks.

At least 1,836 people lost their lives in Hurricane Katrina and in the subsequent floods, making it the deadliest U.S. hurricane since 1928 Okeechobee Hurricane striking the Leeward Island, Puerto Rico, the Bahamas, and Florida on September 1928. The hurricane is estimated to have been responsible for $90.3 billion (2010 U.S. dollars) in damage, making it the costliest natural disaster in U.S. history. Approximately half of the direct economic losses, excluding public and utilities infrastructure, can be associated with breaching of levees and floodwalls.

1.2 Objective of the Present Study

The hurricane-induced oscillation (storm surge) of bays, harbors, and lakes can have a direct effect on shipping and design of flood protection system for beach and coastal communities. Inundation in both estuarine tidal flats and riverine flood planes due to the storm surge not only causes casualties and property damages but also affects the deposition and erosion of sediments in the coastal areas. Predictions of flooding due to storm surge, dam breaching, or levee overtopping are crucial for planning of emergency response.

The shallow-water equations are generally applied to simulate overland flow, lake and river hydrodynamics, long wave run-up, and coastal and estuarine circulations. Researchers have developed various analytical and numerical models based on the depth-averaged, shallow-water equations to describe these phenomena. Although analytical techniques provide exact solutions for idealized geometry and offer insights into the physical phenomena, numerical methods, conversely, provide approximate solutions in more general settings suitable for many practical applications.

The finite-volume method (FVM) solves the integral form of the shallow-water equations in computational cells. The shallow-water equations in the integral form apply to each computational cell, as well as to the solution domain as a whole. After summing up equations for all computational cells, the mass and momentum conservations can be achieved in the entire domain. Therefore, global conservation is built into the method and this provides one of its principal advantages.

The major objective of this research is to investigate the oscillations of semi-enclosed water body induced by hurricanes. The depth-averaged, non-linear shallow-water equations (NLSW) are used to analyze storm surge (oscillation) in a semi-enclosed lake induced by a hurricane. Because conservation of mass and momentum is crucial in simulating the oscillations in a semi-enclosed lake induced by strong winds, the finite-volume method (FVM) is used to solve the depth-averaged, non-linear shallow-water equations in this study. The extensive field data available from Lake Pontchartrain area are used for the comparison with the computational results generated from the present numerical model. Therefore, the water surface elevations (WSE) calculated by the present numerical model at various locations along and in Lake Pontchartrain are verified by the water surface elevations (WSE's) corresponding to these locations estimated or measured by the local, state, and federal agencies during Hurricane Katrina. The essential-meteorological data to re-generate Hurricane Katrina and the field-observatory and the instrument-recorded water surface elevations (WSE's) at Lake Pontchartrain are obtained from the "Performance Evaluation of the New Orleans and Southern Louisiana Hurricane Protection System" report dated June 1, 2006 made by the Interagency Performance Evaluation Task Force (IPET). After the validity of the computational results is complete, the present model is further applied to simulate the oscillation phenomena happening in Lake Pontchartrain induced by four (4) synthetic hurricanes, including Hurricane Katrina.

1.3 Scope of the Present Study

Chapter 2 presents studies using the FVM to solve the depth-averaged, non-linear shallow-water equations (NLSW). The derivation of the FVM model to simulate the wind-induced oscillations in a semi-enclosed lake governed by the depth-averaged, non-linear shallow-water equations (NLSW) is presented in Chapter 3. In the first part of Chapter 4, the present model is verified through the comparison of the simulated hydrographs with the measured hydrographs for eight (8) distinct sites along the shores and the center of Lake Pontchartrain as Hurricane Katrina progressed over the Southeast Louisiana region. In the second part of Chapter 4, the 24-hour contours of the WSE in entire Lake Pontchartrain computed by the present model are used to investigate the oscillation phenomena in Lake Pontchartrain induced by wind generated by four (4) synthetic hurricanes, including Hurricane Katrina. The conclusions of this research are stated in Chapter 5.

Chapter 2: Literature Survey

2.1 Studies Related to Modeling Shallow-Water Flows with Finite-Volume Method

Several numerical schemes are available to solve the depth-averaged, non-linear shallow-water equations (NLSW). There are three (3) widely used methods: the finite-difference method (FDM), the finite-element method (FEM), and the finite-volume method (FVM). FVM becomes more popular in solving the depth-averaged, non-linear shallow-water equations (NLSW) in recent years. In this research, FVM is used because of the following merits:

1. FVM can be considered as a FDM applied to the differential form of the conservation equation while FVM itself is based on the integral form of the conservation equation.
2. The computational effect needed for FVM is less than that for FEM.
3. The mass and momentum can be conserved by discretization of the integral form of the conservation equations.

Zhao et al. (1994) presented a FVM model simulating two-dimensional river-basin flow governed by the depth-averaged shallow-water equations. This two-dimensional unsteady-flow model, called RBFFVM-2D, uses the FVM with Osher scheme (a method based on characteristic theory and a monotone upwind high resolution numerical scheme) by solving a Riemann problem. The river-basin flow is subdivided by unstructured grids using a combination of either triangular elements or quadrilateral elements. Since Osher scheme is an explicit scheme, the model (named RBFFVM-2D) suffers from the requirement of small computation time steps, which depend on the Courant-Friedrichs-Lewy (CFL) condition (or simply called Courant Condition) for numerical stability. Also, Osher scheme is only 1st order accurate in terms of truncation error and consequently the model introduces some numerical damping.

Zhao et al. (1996) presented three approximate Riemann solver schemes based on the characteristic theory: the flux vector splitting (FVS), the flux difference splitting (FDS), and Oscher scheme, which are used in the FVM for solving the two-dimensional shallow water equations. Since all of these algorithms are formulated as explicit schemes, they suffer from the requirement of small computation time steps as dictated by CFL (or Courant) condition for numerical stability. When the grid was refined, it was necessary to reduce the time-step size also, but the relationship is not linear. The analysis also indicated that the solutions were sensitive to the abrupt change of the bottom elevation. Thus, when these schemes are applied, the large bed slope between elements should be avoided or some special treatments for the bed slope term may be needed.

Mingham and Causon (1998) presented a high-resolution Godunov-type FVM for solving the two-dimensional shallow-water equations. The second-order accuracy method uses

Monotonic Upstream Schemes for Conservation Laws (MUSCL) reconstruction and a simple but robust HLL-type (Harten-Lax-van Leer) approximate Riemann solver. Mingham and Causon claim that this method is generally simpler to implement than FVMs based on FVS or FDS approaches and it can be implemented on an arbitrary curvilinear boundary-conforming mesh in order to map complex topography. Mingham and Causon also claim that this model can be used for steady or unsteady flow simulations.

Hu et al. (1998) presented a high-resolution finite volume hydrodynamic solver for open-channel flow governed by the two-dimensional shallow-water equations. A Godunov-type upwind scheme is used for the convective inviscid terms where most of the numerical problems arise. Second-order accuracy is achieved by using Monotonic Upstream Schemes for Conservation Laws (MUSCL) reconstruction in conjunction with a Hancock two-stage scheme for the time integration. An efficient HLL-type (Harten-Lax-van Leer) approximate Riemann solver has been used instead of the more expensive exact Riemann solver. Hu et al. claim that this scheme is robust and capable of simulating supercritical flows and capturing hydraulic jumps. Hu et al. also claim that this scheme introduce little spurious artificial viscosity and has excellent numerical stability.

Hu et al. (2000) presented a finite volume solver together with a Godunov-type upwind scheme. The robust HLL-type approximate Riemann solver has been used instead of the more expensive exact Riemann solver. The model, named AMAZON, is based on solving the non-linear shallow-water (NLSW) equations. This finite volume model, Hu et al. claim, is capable of simulating storm waves propagating in a coastal surf zone and overtopping a sea wall. Hu et al. claim that the advantages of their NLSW model are that it is topographically flexible compared to an empirical model and computationally efficient compared to a three-dimensional model for solving the Navier-Stokes equations. Based on the results from their tests, Hu et al. also claim that a finite volume implementation permits the use of a coarse grid foreshore and fine grid onshore for maximum computational efficiency.

Bradford and Sanders (2002) presented a FVM model developed for unsteady, two-dimensional, shallow-water flow over arbitrary topography with lateral boundaries caused by flooding or recession. This model uses Roe's approximate Riemann solver to compute fluxes, while the MUSCL and Predictor-Corrector time stepping are used to provide a 2^{nd} order accuracy solution that is free from spurious oscillation. Bradford and Sanders affirm that the FVM coupled with MUSCL data reconstruction and a Riemann solver to compute the interfacial fluxes is an accurate and robust approach for solving the shallow-water equations. Bradford and Sanders claim that their proposed model has been successfully applied to the dry bed dam-break problem as well as long wave run-up in one and two-dimensions, which are among the most difficult problems with moving dry/wet boundaries.

Wei et al. (2006) presented a two-dimensional, well-balanced finite-volume model for run-up of long waves under non-breaking and breaking conditions. Their model uses the surface-gradient method and a Godunov-type scheme with an exact Riemann solver to track the moving waterline and to capture flow discontinuities associated with bores or breaking waves, which are essential for run-up calculations. Furthermore, their model uses an explicit second-order splitting scheme for the time integration and achieves 2nd order accuracy in space through a piecewise linear interpolation of conserved variables and this approach provides good shock-capturing capability as well as accurate descriptions of the flow near the moving waterline. Wei et al. claim that their model provides accurate predictions of non-breaking and breaking wave run-up and has potential applications in flood hazards mitigation.

Among these previous studies, turbulent viscosity terms, i.e. $\nu_T \nabla^2 u$, are cancelled out from the governing shallow-water equations except that Hu et al. (1998) kept these terms in their model. During the verification of their model, turbulent viscosity terms were no longer taken into account because of the physical mechanisms of their test problems. It is necessary to examine the role of turbulent viscosity terms in the shallow-water equations, to demonstrate the reasons to eliminate them, to validate their importance in this proposed research, and further to search either available empirical formulae or available turbulence models according to physical characteristics of eddy viscosity, ν_T, to compute $\nu_T \nabla^2 u$ whenever solving the non-linear, depth-averaged shallow-water equations (NLSW).

2.2 Role of Eddy Viscosity in Shallow-Water Equations

Turbulent viscosity terms, i.e. $\nu_T \nabla^2 u$, represent the momentum exchange and energy dissipation resulting from molecular diffusion, turbulent diffusion, vertical variation of horizontal velocity, and non-uniformity of the velocity distribution over the horizontal plane.

The concept of eddy viscosity (or eddy diffusivity) was proposed by Boussinesq at 1877

$$-\overline{uv} = \nu_T \frac{dU}{dy} \tag{2.1}$$

where $-\rho\overline{u_i u_j}$ is called the Reynolds stresses and the eddy viscosity (or turbulent exchange coefficient for momentum) can be defined as

$$\nu_T \sim u' l_m \tag{2.2}$$

where u' is a typical scale of the fluctuating velocity, and l_m is the mixing length, defined as the cross-stream distance traveled by a fluid particle before it gives up its momentum and loses identity.

The turbulent stress in the non-linear, depth-averaged shallow-water equations is composed of three (3) parts:

1. Molecular viscosity stress is small in magnitude except in a very thin layer.
2. Horizontal turbulent normal stresses (τ_{xx} and τ_{yy}) come from integrating the three-dimensional Navier-Stokes equations over time to get the three-dimensional Reynolds equations.
3. Horizontal turbulent shear stresses (τ_{yx} etc.) come from integrating the three-dimensional Reynolds equations over depth to get the non-linear, depth-averaged shallow-water equations.

These terms play an important role in the shallow-water equations because:

1. As an internal resistance to the flow, they dissipate energy and consequently are favorable for stabilizing both physical and numerical solutions.
2. Whenever used together with the convective term, simulation of vortices and circulations becomes possible.

Most numerical models solving the depth-averaged, non-linear shallow-water equations (NLSW) completely neglect turbulent viscosity, or include it only in the bottom friction term. The main reason is that turbulent viscosity predominantly originates from disturbances appearing at the top and bottom interfaces, which have been accounted for by surface wind stress τ^{η} and bottom stress τ^{-h}.

The general form of the momentum equation is:

$$\rho \frac{D\vec{u}}{Dt} = \rho \frac{\partial \vec{u}}{\partial t} + \rho \vec{u} \cdot \nabla \vec{u} = -\nabla p + \mu \Delta \vec{u} \tag{2.3}$$

Then we can take curl of (2.3) to get the general form of the vorticity equation:

$$\frac{\partial \vec{\varpi}}{\partial t} + \nabla \times \left(\vec{u} \cdot \nabla \vec{u} \right) = -\nabla \times \left(\frac{1}{\rho} \nabla p \right) + \nu \Delta \vec{\varpi} \tag{2.4}$$

The second term in (2.4), $\nabla \times \left(\vec{u} \cdot \nabla \vec{u} \right)$, can be rewritten as follows:

$$\begin{aligned} \nabla \times (\vec{u} \cdot \nabla \vec{u}) &= \frac{1}{2} \nabla \times (\nabla (\vec{u} \cdot \vec{u})) - \nabla \times (\vec{u} \times \vec{\varpi}) = -\vec{u}(\nabla \cdot \vec{\varpi}) + \vec{\varpi}(\nabla \cdot \vec{u}) + (\vec{u} \cdot \nabla)\vec{\varpi} - (\vec{\varpi} \cdot \nabla)\vec{u} \\ &= (\vec{u} \cdot \nabla)\vec{\varpi} - (\vec{\varpi} \cdot \nabla)\vec{u} \end{aligned} \tag{2.5}$$

Thus, we can obtain the general form of the vorticity-transport equation:

$$\frac{D\vec{\varpi}}{Dt} = \frac{\partial \vec{\varpi}}{\partial t} + \vec{u} \cdot \nabla \vec{\varpi} = \vec{\varpi} \cdot \nabla \vec{u} + \nu \Delta \vec{\varpi} \tag{2.6}$$

$\vec{\varpi} \cdot \nabla \vec{u}$ is called the vortex stretching term. For two-dimensional flow, this term is vanquished. Finally, the general form of the two-dimensional vorticity-transport equation is:

$$\frac{D\vec{\varpi}}{Dt} = \nu \Delta \vec{\varpi} \tag{2.7}$$

Since no physical mechanism of vortex stretching would exist in two-dimensional flow, according to (2.7), turbulence can no longer be preserved. Furthermore, since turbulent viscosity in the two-dimensional, non-linear shallow-water equations has a depth-averaging sense, its value is more or less different from that in the three-dimensional flow. However, the relevant law has not yet been fully formulated.

Stansby (2003) investigated the influence of horizontal diffusion for a range of recirculating wake flows. He applied the three-dimensonal shallow-water equations in (partially) conservative form with the assumption of hydrostatic pressure, which is assumed to be justified for bed (and free-surface) topographies of small slope. A staggered mesh is used within a finite-volume approach. In the momentum equations,

second-order Crank-Nicolson time stepping is used for surface elevation gradient terms to obtain the horizontal velocities and fully implicit time-stepping is used for vertical diffusion. The stepping for advection and horizontal diffusion is treated explicitly, to second-order accuracy, using the Adams-Bashforth scheme. The QUICK (Quadratic Upwind Interpolation) scheme is used for the spatial discretization of advection.
The basic hypothesis, as Stansdy states, is that vertical turbulent length scales are smaller than the horizontal scales. The mixing-length approach for boundary-layer definition in the vertical is extended to the horizontal by assuming that there is a horizontal mixing length which is a constant multiple of the vertical value at a given elevation, thus giving an eddy viscosity based on two scales. Stansby also states that an assumption of turbulence modeling is that the turbulence length scales are smaller than the larger scale flow structures which are computed directly.

In conclusion, Stansby states that horizontal mixing affects the vertical variation of velocity, which in turn affects bed shear. Furthermore, Stansby claims that horizontal mixing causes the friction coefficient to be increased where vorticity is present. Therefore, dispersion is either omitted or a standard vertical variation of velocity is assumed which can not take into account horizontal diffusion. However, Stansby claims that flows with stable wakes or strong vortex shedding are relatively insensitive to horizontal diffusion and suitably calibrated depth-averaged models can be a useful role with the advantage of being very computationally efficient.

In this research, the wind-induced oscillation in a lake is modeled using the depth-averaged, non-linear shallow-water equations and the wind-shear stresses imposed on the surface of the lake is the dominant forcing mechanism to cause the oscillation in the lake; hence, this wind-driven shear flow in a lake will be highly-turbulent and consequently it is necessary not to eliminate the turbulent viscosity terms, i.e. $\nu_T \nabla^2 u$, in the non-linear, depth-averaged shallow-water equations, as opposite to other numerical models for solving the non-linear, depth-averaged shallow-equations. In order to simulate the physical characteristics of the oscillation governed by the wind-driven shear flow in a lake in a more realistic sense, the eddy viscosity, ν_T, used in the present study is a time-variant variable (10 ~ 100 m^2/s) instead of a commonly-used constant (100 m^2/s, see Kundu & Cohen (2002) and Tan (1992)) imposed in the turbulent viscosity terms, i.e. $\nu_T \nabla^2 u$.

Chapter 3: Theoretical Analysis

In this research, the integral form of the depth-averaged, non-linear shallow-water equations (NLSW) is used to model the wind-induced oscillation. Because the nonlinear shallow-water equations representing the physical mechanisms of the induced oscillation in an arbitrary shaped lake are solved in this study, it is not feasible to use the analytical techniques for solving a system of nonlinear partial differential equations in a complex domain. A numerical scheme, named the finite-volume method (FVM), will be used in this study because:

1. The depth-averaged shallow-water equations are nonlinear.
2. The solution domain is geometrically complex.
3. The conservation of mass and momentum is crucial.

3.1 Governing Equations

In this research, the depth-average shallow-water equations are used to analyze the physical mechanisms of the wind-induced oscillations in semi-enclosed water bodies:

$$\frac{\partial \eta}{\partial t}+\frac{\partial}{\partial x}\left[(h+\eta)u\right]+\frac{\partial}{\partial y}\left[(h+\eta)v\right]=0 \tag{3.1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}-fv=-g\frac{\partial \eta}{\partial x}-\frac{1}{\rho}\frac{\partial p_a(r)}{\partial x}+\nu_T\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\frac{\left(\tau_x^\eta-\tau_x^{-h}\right)}{\rho(h+\eta)} \tag{3.2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+fu=-g\frac{\partial \eta}{\partial y}-\frac{1}{\rho}\frac{\partial p_a(r)}{\partial y}+\nu_T\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{\left(\tau_y^\eta-\tau_y^{-h}\right)}{\rho(h+\eta)} \tag{3.3}$$

in the Cartesian Coordinate system, where $\eta =$ water surface elevation above mean water surface; $h =$ water depth below mean water surface. (u, v) are the depth-averaged horizontal velocity components; $\rho =$ water density; $p_a(r) =$ atmospheric pressure; $\nu_T =$ eddy viscosity; $\left(\tau_x^\eta, \tau_y^\eta\right)$ and $\left(\tau_x^{-h}, \tau_y^{-h}\right)$ = the surface wind stress and the bottom drag components, respectively. f indicates the Coriolis parameter ($f = 2\Omega \sin(\theta)$, where Ω is the angular velocity of the earth and θ is the latitude); and g is the gravitational acceleration.

Surface wind stress terms $\left(\tau_x^\eta, \tau_y^\eta\right)$ represent the drag force produced by wind over the water surface:

$$\tau_x^\eta = \rho_a C_D w_{ax}\sqrt{w_{ax}^2 + w_{ay}^2} \tag{3.4a}$$

$$\tau_y^{\eta} = \rho_a C_D w_{ay} \sqrt{w_{ax}^2 + w_{ay}^2} \tag{3.4b}$$

w_{ax}, w_{ay} denote wind velocities at x and y coordinates, respectively, ρ_a = density of air, and C_D is the drag coefficient. Garratt's drag formula (Garratt 1977) is used to calculate C_D in this study:

$$C_D = (0.75 + 0.067 w_a) \times 10^{-3} = \left(0.75 + 0.067\sqrt{w_{ax}^2 + w_{ay}^2}\right) \times 10^{-3} \tag{3.5}$$

Bottom drag terms $\left(\tau_x^{-h}, \tau_y^{-h}\right)$ have a nonlinear effect of retarding the flow. Since the bottom turbulent stress is not well understood, the bottom drag can be estimated by an empirical formula:

$$\tau_x^{-h} = \rho r_b u \sqrt{u^2 + v^2} \tag{3.6a}$$

$$\tau_y^{-h} = \rho r_b v \sqrt{u^2 + v^2} \tag{3.6b}$$

$r_b = 2.6 \times 10^{-3}$ = the sea bottom friction coefficient.

3.2 Pressure and Wind Fields

A hurricane will harbor an area of sinking air at the center of circulation. This area is known as the eye of the hurricane. The eye is normally circular in shape and weather in the eye is normally calm and free of clouds. Both pressure and wind profiles across the entire hurricane can be meteorologically described in a diagram of the cross-sectional view of a hurricane (Figure 3.1).

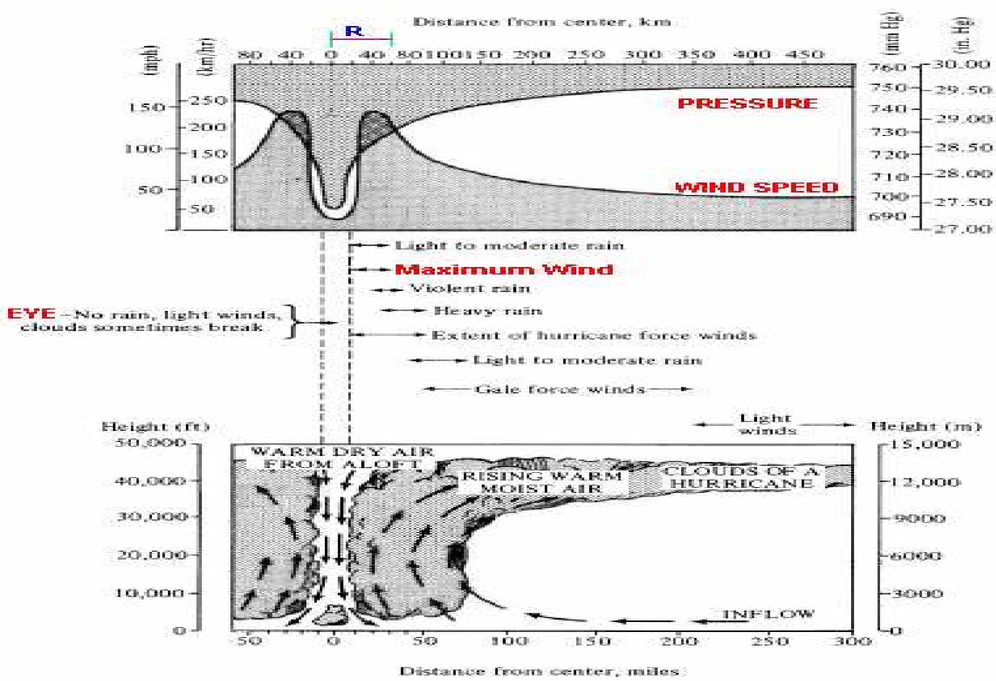

Figure 3.1 Vertical Section of Hurricane (modified from Miller & Thompson, 1970)

An atmospheric pressure field can be developed based either on observation or on forecast. In this study, we will use a pressure field associated with an ideal hurricane model. Two well-known formulae, Fujita and Takahashi Formulae (Tan 1992), can estimate the atmosphere pressure at a distance *r* from the center of a hurricane:

$$p_a(r) = p_\infty - \frac{p_\infty - p_o}{\sqrt{1 + 2(r/R)^2}}, (0 \le r \le 2R) \tag{3.7}$$

$$p_a(r) = p_\infty - \frac{p_\infty - p_o}{1 + r/R}, (2R \le r < \infty) \tag{3.8}$$

where $p_\infty =$ the ambient atmospheric pressure; $p_o =$ pressure at the center of the typhoon; and $R =$ radius of maximum wind speed. The pressure field generated by the combination of these two formulae can yield a reasonable radial pressure distribution (Zhou and Li, 2005).

The total wind field is generated by superposing the convection due to the motion of a hurricane itself

$$V = V_X\, exp\left(-\frac{\pi}{4}\frac{|r-R|}{R}\right) + V_Y\, exp\left(-\frac{\pi}{4}\frac{|r-R|}{R}\right) \tag{3.9}$$

and the gradient pressure field

$$|G| = -\frac{f}{2}r + \sqrt{\frac{f^2}{4}r^2 + \frac{|p_a(r) - p_\infty|}{\rho_a}} \tag{3.10}$$

In this research, we use an ideal hurricane model in association with the total wind field presented by (3.9) and (3.10) and the "quiet" character at the eye of the hurricane. Therefore, the wind velocities at a distance *r* from the center of a hurricane will be:

$$w_{ax,R.E.} = w_{am} \times \frac{w_{ax}}{w_a} \times \frac{r}{R.E.}, (0 \le r \le R.E.) \tag{3.11}$$

$$w_{ay,R.E.} = w_{am} \times \frac{w_{ay}}{w_a} \times \frac{r}{R.E.}, (0 \le r \le R.E.) \tag{3.12}$$

$$w_{ax,r} = c_1 V_X \exp\left(-\frac{\pi}{4}\frac{|r-R|}{R}\right) + c_2 |G| \frac{dy}{r}$$

$$= c_1 V_X \exp\left(-\frac{\pi}{4}\frac{|r-R|}{R}\right) + c_2 \left(\sqrt{\frac{f^2}{4} r^2 + \frac{|p_a(r) - p_\infty|}{\rho_a}} - \frac{f}{2} r\right) \frac{dy}{r} \tag{3.13}$$

$$,(R.E. < r \leq \infty)$$

$$w_{ay,r} = c_1 V_Y \exp\left(-\frac{\pi}{4}\frac{|r-R|}{R}\right) - c_2 |G| \frac{dx}{r}$$

$$= c_1 V_Y \exp\left(-\frac{\pi}{4}\frac{|r-R|}{R}\right) - c_2 \left(\sqrt{\frac{f^2}{4} r^2 + \frac{|p_a(r) - p_\infty|}{\rho_a}} - \frac{f}{2} r\right) \frac{dx}{r} \tag{3.14}$$

$$,(R.E. < r \leq \infty)$$

where $w_a = \sqrt{w_{ax}^2 + w_{ay}^2}$ and $w_{am} = max(w_a)$; c_1 and c_2 are empirical coefficients; V_X and V_Y are x- and y-components, respectively, of the velocity of the typhoon center located at the origin; and $R.E. =$ radius of eye.

3.3 FVM Scheme

The finite-volume method (FVM) is applied to the integral form of the shallow-water equations as a starting point:

$$\frac{\partial}{\partial t}\int_{\Omega}\rho\Phi d\Omega+\int_{\Omega}\frac{\partial(\rho u_j\Phi)}{\partial x_j}d\Omega=\frac{\partial}{\partial t}\int_{\Omega}\rho\Phi d\Omega+\int_{S}\rho\Phi u\cdot ndS$$
$$=\int_{\Omega}\frac{\partial}{\partial x_j}\left(\Gamma\frac{\partial\Phi}{\partial x_j}\right)d\Omega+\int_{\Omega}q_{\Phi}d\Omega=\int_{S}\Gamma grad\Phi\cdot ndS+\int_{\Omega}q_{\Phi}d\Omega \tag{3.15}$$

where Φ = conserved variables; Ω = control volume; S = boundary; n = outward normal vector; Γ = thermodynamic properties; and q_{Φ} = sources terms.

The solution domain is subdivided into a finite number of small control volumes (CVs) by a grid that defines the control volume (CV) boundaries. In this study, we define control volumes (CVs) by a suitable grid and assign the computational node to the center of each control volume (CV). The advantage of this approach is that the node value represents the mean that can have a second order accuracy over the control volume (CV).

The integral shallow-water equations shown by (3.15) apply to each control volume (CV), as well as to the solution domain as a whole. After we sum up equations for all control volumes (CVs), the global conservation of mass and momentum can be obtained since the surface integrals over inner control volume (CV) faces can be cancelled out. A typical grid structure of the finite-volume method (FVM) is shown on Figure 3.2.

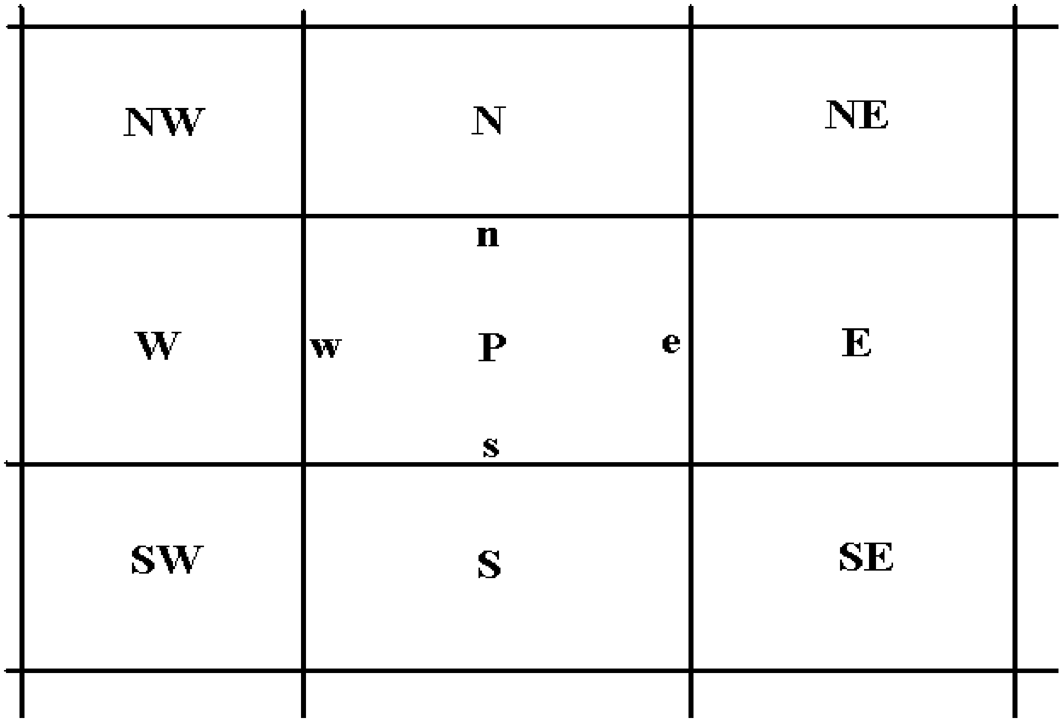

Figure 3.2 A Typical CV and the Notation used for a Cartesian 2D Grid

By applying the divergence theorem to (3.15) and summing up all source terms, we can produce an algebraic equation which relates the variable value at the center of a particular control volume (CV) denoted by $|\Omega|$ to the variable values at several neighbor control volumes (CVs)

$$\frac{d(\rho\Phi)}{dt} = \frac{1}{|\Omega|}\int_S \left(-\rho\Phi u + \Gamma grad\Phi\right)\cdot n dS + q_\Phi \tag{3.16}$$

The numbers of equations and unknowns are both equal to the numbers of control volumes (CVs) so the system is well-posed. The algebraic equation for a particular control volume (CV) has the following form:

$$A_P \Phi_P + \sum_l A_l \Phi_l = Q_P \tag{3.17}$$

where P denotes the center of the control volume (CV) and index l runs over the boundary surfaces of the control volume (CV) and the system of algebraic equations for the whole solution domain has the matrix form given by

$$A\,\Phi = Q \tag{3.18}$$

In this research, uniform rectangular control-volumes (CV's) with dimensions $(\Delta x, \Delta y)$ in a Cartesian grid and a time-step Δt are used. In order to obtain the second-order accuracy in the spatial derivatives, the central-differential scheme (CDS) is applied to the spatial derivatives. Because time accuracy is of crucial importance in the study of the wind induced-oscillation (so called storm surge) in a semi-enclosed lake, the second order accuracy of the trapezoid rule method, named the Crank-Nicolson method, is used to discretize the "time" coordinate.

By applying the Crank-Nicolson method to the shallow-water equations in the form of (3.16) with central-difference scheme (CDS) for the spatial derivatives, we can obtain:

$$\begin{aligned}\Phi_{i,j}^{n+1}=\Phi_{i,j}^{n}&+\frac{\Delta t}{2}\left[-u\frac{\Phi_{i+1,j}^{n+1}-\Phi_{i-1,j}^{n+1}}{2\Delta x}-v\frac{\Phi_{i,j+1}^{n+1}-\Phi_{i,j-1}^{n+1}}{2\Delta y}+\frac{\Gamma}{\rho}\frac{\Phi_{i+1,j}^{n+1}-2\Phi_{i,j}^{n+1}+\Phi_{i-1,j}^{n+1}}{(\Delta x)^2}+\frac{\Gamma}{\rho}\frac{\Phi_{i,j+1}^{n+1}-2\Phi_{i,j}^{n+1}+\Phi_{i,j-1}^{n+1}}{(\Delta y)^2}\right]\\&+\frac{\Delta t}{2}\left[-u\frac{\Phi_{i+1,j}^{n}-\Phi_{i-1,j}^{n}}{2\Delta x}-v\frac{\Phi_{i,j+1}^{n}-\Phi_{i,j-1}^{n}}{2\Delta y}+\frac{\Gamma}{\rho}\frac{\Phi_{i+1,j}^{n}-2\Phi_{i,j}^{n}+\Phi_{i-1,j}^{n}}{(\Delta x)^2}+\frac{\Gamma}{\rho}\frac{\Phi_{i,j+1}^{n}-2\Phi_{i,j}^{n}+\Phi_{i,j-1}^{n}}{(\Delta y)^2}\right]+\frac{q_{\Phi}(\Delta t)}{\rho}\end{aligned} \quad (3.19)$$

The above equation can be written as:

$$A_P\Phi_{i,j}^{n+1}+A_W\Phi_{i-1,j}^{n+1}+A_E\Phi_{i+1,j}^{n+1}+A_S\Phi_{i,j-1}^{n+1}+A_N\Phi_{i,j+1}^{n+1}=Q_{i,j}^{t} \quad (3.20)$$

where:

$$A_W=-\frac{\rho u}{4\Delta x}-\frac{\Gamma}{2(\Delta x)^2} \quad (3.21)$$

$$A_S=-\frac{\rho v}{4\Delta y}-\frac{\Gamma}{2(\Delta y)^2} \quad (3.22)$$

$$A_E = \frac{\rho u}{4\Delta x} - \frac{\Gamma}{2(\Delta x)^2} \tag{3.23}$$

$$A_N = \frac{\rho v}{4\Delta y} - \frac{\Gamma}{2(\Delta y)^2} \tag{3.24}$$

$$A_P = \frac{\rho}{\Delta t} - (A_E + A_W + A_N + A_S) \tag{3.25}$$

$$\begin{aligned} Q^t_{i,j} &= \left(\frac{\rho}{\Delta t} + A_E + A_W + A_N + A_S\right)\Phi^n_{i,j} \\ &- A_E \Phi^n_{i+1,j} - A_W \Phi^n_{i-1,j} - A_N \Phi^n_{i,j+1} - A_S \Phi^n_{i,j-1} + q_\Phi \end{aligned} \tag{3.26}$$

The term $Q^t_{i,j}$ represents an "additional" source term, which contains the contribution from the previous time step; it remains constant during iterations at the new time step. The equation can also contain a source term dependent on the new solution, so $Q^t_{i,j}$ will be stored separately.

3.4 Boundary and Initial Conditions

Since the currents are generated at rest, we will approximately assume that $u = v = 0$ everywhere in the lake as the initial condition. The initial water surface elevation (WSE) denoted as η is set to the hydrostatic height corresponding to the initial pressure field.

Along the lake shore, the impervious boundary condition (so called wall condition), that is both no-slip and no-through, is applied, i.e. $u = v = 0$. However, there is another condition that can be directly imposed in a finite-volume method (FVM); the normal viscous stress is zero at a wall. This can be derived from the continuity equation, e.g. for a wall at $y = 0$

$$\left(\frac{\partial u}{\partial x}\right)_{wall} = 0 \Rightarrow \left(\frac{\partial v}{\partial y}\right)_{wall} = 0 \Rightarrow \tau_{yy} = 2\nu_H \left(\frac{\partial v}{\partial y}\right)_{wall} = 0 \tag{3.27}$$

Therefore, the diffusive flux in the v equation at $y = 0$ is zero. This should be implemented directly, rather than using only the condition that $v = 0$ at the wall.

At an open boundary, the Dirichlet boundary condition is applied as the WSE at that open boundary is set to the prescribed hydrostatic height. The shear stress is zero at an open boundary (O.B.), e.g. at $y = 0$

$$\left(\frac{\partial u}{\partial y}\right)_{O.B.} = 0 \tag{3.28}$$

Therefore, the diffusive flux in the *u* equation is zero and this should be implemented directly.

Chapter 4: Presentation and Discussion of Results

4.1 Meteorological Background

Hurricane Katrina formed as Tropical Depression Twelve (12) over the southeastern Bahamas on August 23, 2005 as the results of an interaction of a tropical wave and the remains of Tropical Depression Ten (10). The system was upgraded to tropical storm status on the morning of August 24 and at this point, the storm was given the name Katrina. The tropical storm continued to move towards Florida, and became a hurricane only two hours before it made landfill between Hallandale Beach and Aventura, Florida on the morning of August 25. The storm weakened over land, but it regained hurricane status about one hour after entering the Gulf of Mexico.

The storm rapidly intensified after entering the Gulf, partly because of the storm's movement over the warm water of the Loop Current. On August 27, the storm reached Category 3 intensity on the Saffir-Simpson Hurricane Scale, becoming the third major hurricane of the season. Katrina again rapidly intensified, attaining Category 5 status on the morning of August 28 and reached its peak strength at 1:00 p.m. CDT that day, with maximum sustained winds of 175 mph (280 km/h) and a minimum central pressure of 902 mbar. The pressure measurement made Katrina the fourth most intense Atlantic hurricane on record at the time. The aerial photo of Hurricane Katrina taken by the

National Oceanic and Atmospheric Administration (NOAA) is shown on Figure 4.1. It can be seen that the enormous extent of Katrina can overlay the northeast part of the Gulf of Mexico with several states, such as Alabama, Louisiana and Mississippi, along the Gulf from Figure 4.1.

Figure 4.1 A Satellite Image of Hurricane Katrina (adopted from NOAA)

Katrina made its second landfall at 6:10 a.m. CDT August 29 as a Category 3 hurricane with sustained winds of 125 mph (205 km/h) near Buras-Triumph, Louisiana. At landfall, hurricane-forced winds extended outward 120 miles (190 km) from the center and the storm's center pressure was 920 mbar. After moving over southeastern Louisiana and Breton Sound, it made its third landfall near the Louisiana/Mississippi border with the wind speed of 120 mph (195km/h), still at Category 3 intensity.

Katrina maintained strength well into Mississippi, finally losing hurricane strength more than 150 miles (240 km) inland near Meridian, Mississippi. It was downgraded to a tropical depression near Clarksville, Tennessee, but its remnants were last distinguishable in the eastern Great Lakes region on August 31, when it was absorbed by a frontal boundary. The resulting extra-tropical storm moved rapidly to the northeast and affected Ontario and Quebec (Knabb et al. 2006). The map showing the origin and finale of Katrina accompanying with its path is presented on Figure 4.2.

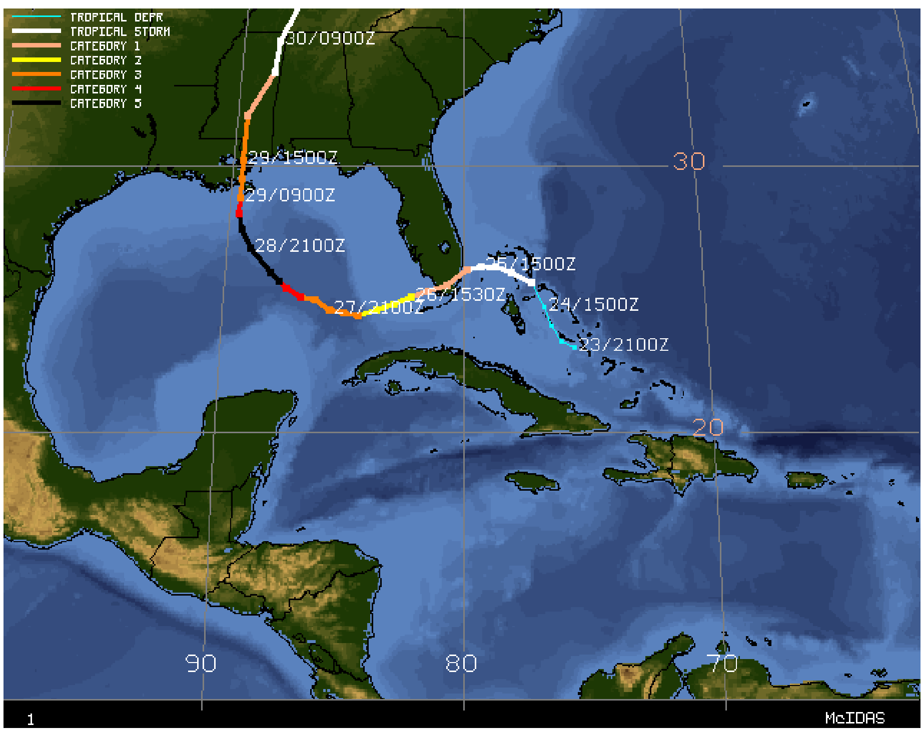

Figure 4.2 The Storm Path of Hurricane Katrina (based on Knabb et al. 2006)

4.2 Geographic Background

Lake Pontchartrain is an estuary which connects with the Gulf of Mexico via Rigolets strait and Chef Menteur Pass into Lake Borgne, and therefore experiences small tidal changes. It receives fresh water from Tangipahoa, Tchefuncte, Tickfaw, Amite, and Bogue Falaya Rivers, and from Bayou Lacombe. Lake Maurepas connects with Lake Pontchartrain on the west via Pass Manchac. The Industrial Canal connects the Mississippi River with the lake at New Orleans. Bonnet Carre Spillway diverts water from the Mississippi River into the lake during times of river flooding. The lake was created 2,600 to 4,000 years ago as the evolving Mississippi River Delta formed its southern and eastern shorelines with alluvial deposits. The aerial photo showing Lake Pontchartrain and several important landmarks along and within the lake is presented on Figure 4.3.

Figure 4.3 A Satellite Image of Lake Pontchartrain

New Orleans was established at a Native American portage between the Mississippi River and Lake Pontchartrain. In the 1920s the Inner Harbor Navigation Canal (IHNC, so called Industrial Canal locally) in the eastern part of the city opened, providing a direct navigable water connection, with locks, between the Mississippi River and the lake. In the same decade, a project dredging new land from the lake shore behind a new concrete floodwall began and this would result in an expansion of the city into the swamp between Metairie/Gentilly Ridges and the lakefront. The Lake Pontchartrain Causeway, about 24 miles (39 km) long, was constructed in the 1950s and 1960s, connecting New Orleans (by way of Metairie) with Mandeville and bisecting the lake in a north-northeast line. The Causeway is the longest bridge over a body of water in the world. The aerial photo showing the City of New Orleans with surrounding communities taken by the National Aeronautics and Space Administration (NASA) is presented on Figure 4.4.

Figure 4.4 A Satellite Image of New Orleans, Louisiana

Although Katrina weakened to a Category 3 before making landfall on August 29 (with only Category 1-2 strength winds in New Orleans on the weaker side of the eye of the hurricane), the outlying New Orleans East along south Lake Pontchartrain was in the eyewall with winds, preceding the eye, nearly as strong as Bay St. Louis, Mississippi. Some canals began leaking at 8 a.m. CDT (Chalmette, Louisiana) and some levees/canals, designed to withstand Category 3 storms, suffered multiple breaks the following day, flooding 80% of the city.

The walls of the Inner Harbor Navigation Canal (IHNC) were breached by storm surge via the Mississippi River Gulf Outlet (MRGO), while the 17th Street Canal and the London Avenue Canal experienced catastrophic breaches, even though water levels never topped their flood walls. Aerial photography suggests that 25 billion gallons (95 billion liters) of water covered New Orleans as of September 2, which equals about 2% of Lake Pontchartrain's volume. It can be seen that New Orleans and the surrounding communities were severely damaged by the catastrophic floods caused by Hurricane Katrina from Figures 4.5 and 4.6.

Figure 4.5 An Aerial View of the Flooding In Part of The Central Business District

Figure 4.6 Flooded I-10/I-610 Interchange and Surrounding of Northwest New Orleans and Metairie, Louisiana

4.3 On-Site Measurement Data

An intense performance evaluation of the New Orleans and Southeast Louisiana hurricane protection system during Hurricane Katrina was conducted by the Interagency Performance Evaluation Task Force (IPET), a distinguished group of government, academic, and private sector scientists and engineers who dedicated themselves solely to this task which is formed shortly after Katrina struck. A nine-volume final report, designed to provide a detailed documentation of the technical analyses conducted and their associated findings, was published on June 1, 2006. Volume IV, named The Storm, in this final report made by the Interagency Performance Evaluation Task Force (IPET) presents the regional hydrodynamic conditions created by Katrina (waves and water levels). Local waves and water levels, in both maximum conditions and temporal variation, at the levees and the floodwalls are presented in Volume IV, titled The Storm, of this final report.

Measured water levels fell into two categories, high water mark measurements that capture peak water levels and hydrographs which capture the water level as a function of time. An extensive post-storm effect was undertaken to identify and survey high water marks following passage of the storm. While certain high water marks capture the peak water levels well, they contain no information about the temporal variation of water level.

Measured hydrographs are the most reliable source of data for capturing both the temporal variation and the maximum level. Water level fluctuations were measured with instruments during the build-up stage of the storm at several sites throughout New Orleans and Southeast Louisiana region. However, few instruments operated throughout the storm and most of them failed prior to the peak. Consequently, little measured data that captures peak conditions is available. At a few sites, photographs and other visual observations were used to provide information about the temporal variation of water level to finalize the construction of these recorded hydrographs. These constructed hydrographs are extremely valuable to study the oscillations along the south shore of Lake Pontchartrain induced by wind generated by Hurricane Katrina.

Time-tagged digital images from the Lake Pontchartrain – New Orleans lakefront were taken by several individuals during Katrina's passage. Using these images, logs of observations, and nearby high water marks, hydrographs of the 17th Street Canal entrance and the New Orleans Lakefront Airport were constructed. Recorded and constructed hydrographs are presented in the following paragraphs.

A map showing various sites along and in Lake Pontchartrain is presented on Figure 4.7. Five gauged hydrographs and two constructed hydrographs are presented in Figure 4.8. Each hydrograph is labeled with a relative locality along and in Lake Pontchartrain as west, central, or east. The constructed hydrographs are for the 17th Street Canal and the Lakefront Airport, and the gage hydrographs are for Southshore Marina, Little Irish Bayou, Pass Manchac, and Bayou Labranch. The Midlake Gage was adjusted to North America Vertical Datum of 1988 (NAVD88) by matching the average of the Pass Manchac and Bayou Labranch gage hydrographs before the storm. Hydrographs were constructed for the entrances of Orleans Avenue Canal, London Avenue Canal, and the IHNC by using the best estimate peak water levels at the entrances of these canals along with the constructed hydrographs at the 17th Street Canal and the Lakefront Airport. The interpolated hydrographs for the Orleans Canal, London Canal, and IHNC are generally plotted on Figure 4.9 and are plotted in detail on Figure 4.10.

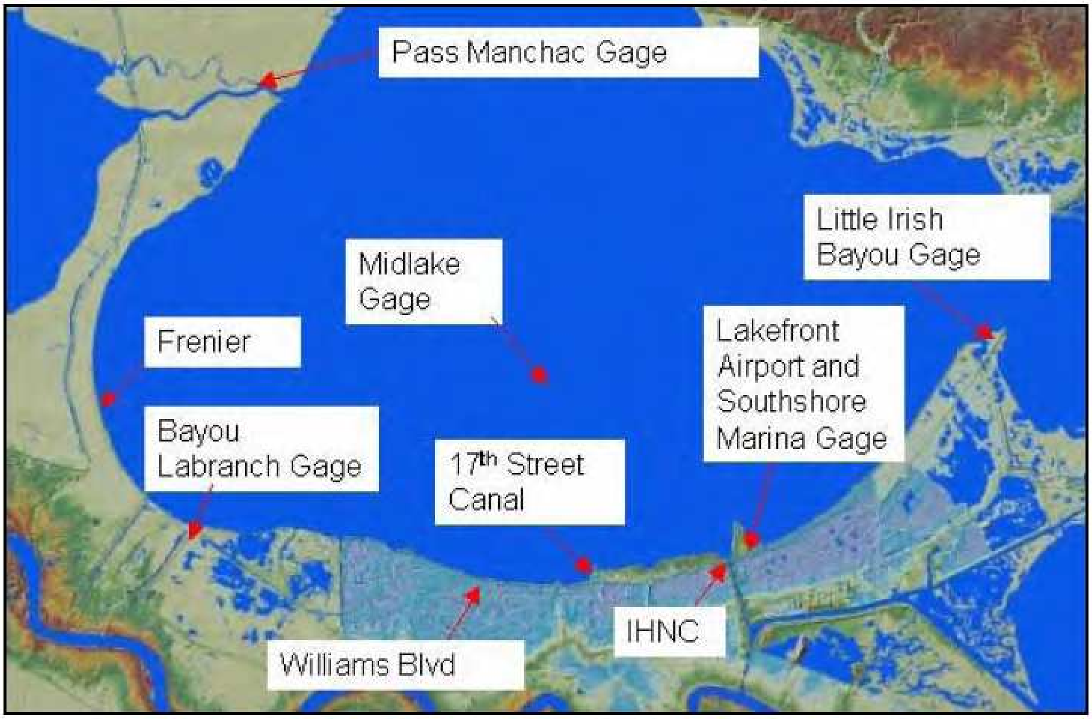

Figure 4.7 Lake Pontchartrain Gages and Other Locations Referenced in IPET Report

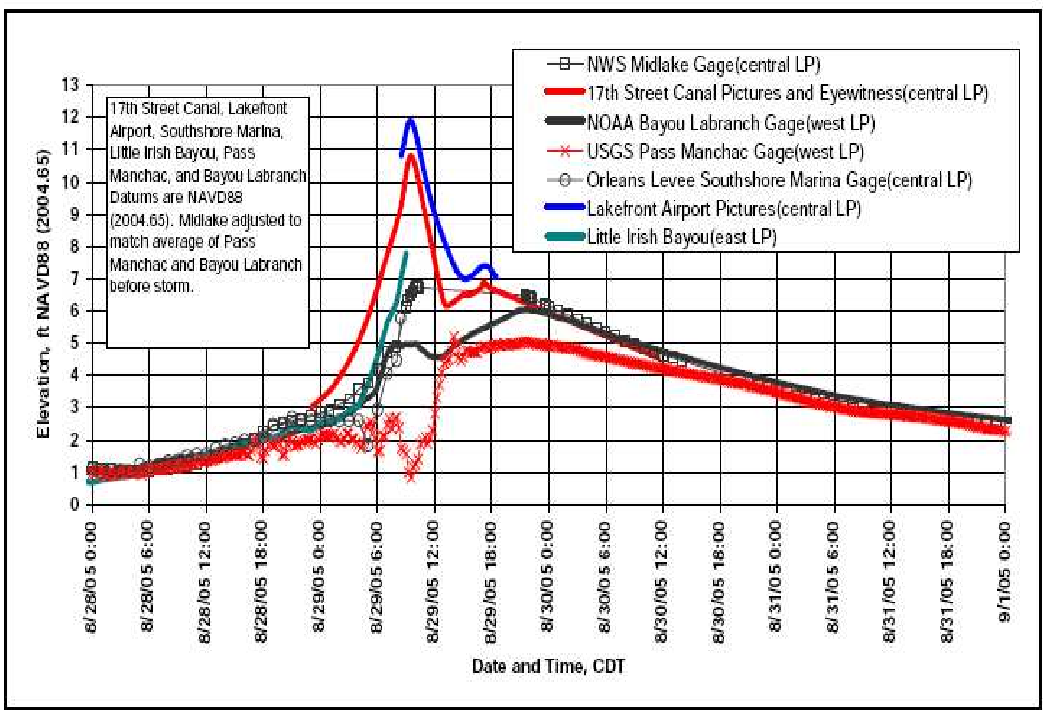

Figure 4.8 Gage Hydrographs and Constructed Hydrographs on Lake Pontchartrain

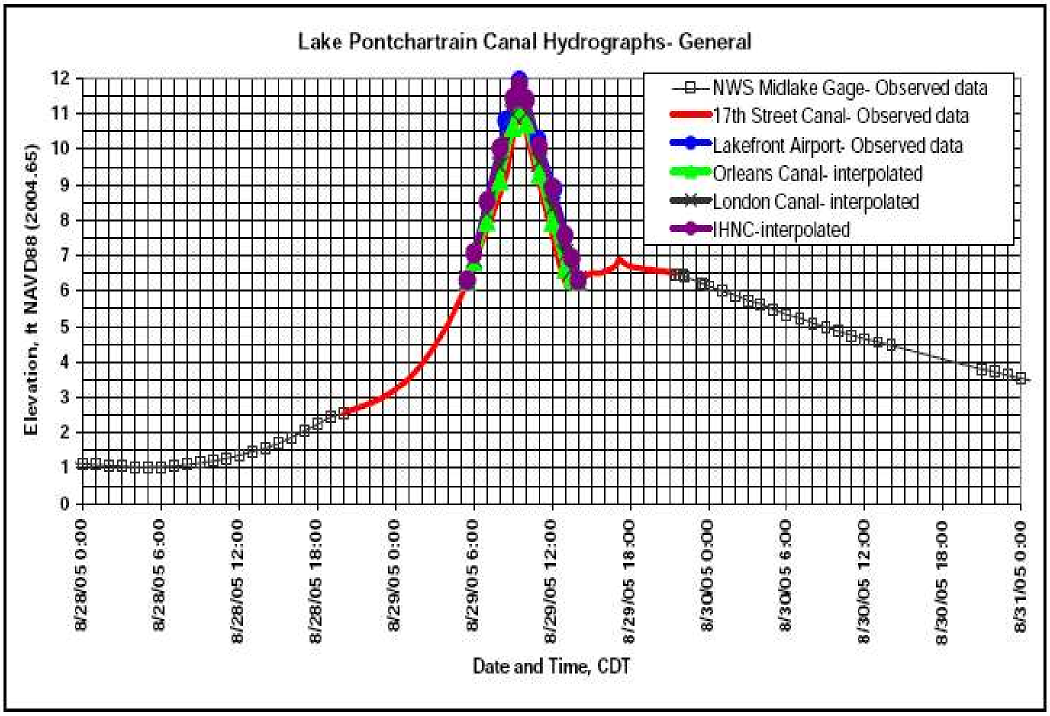

Figure 4.9 Constructed and Interpolated Hydrographs at Canal Entrances-General View

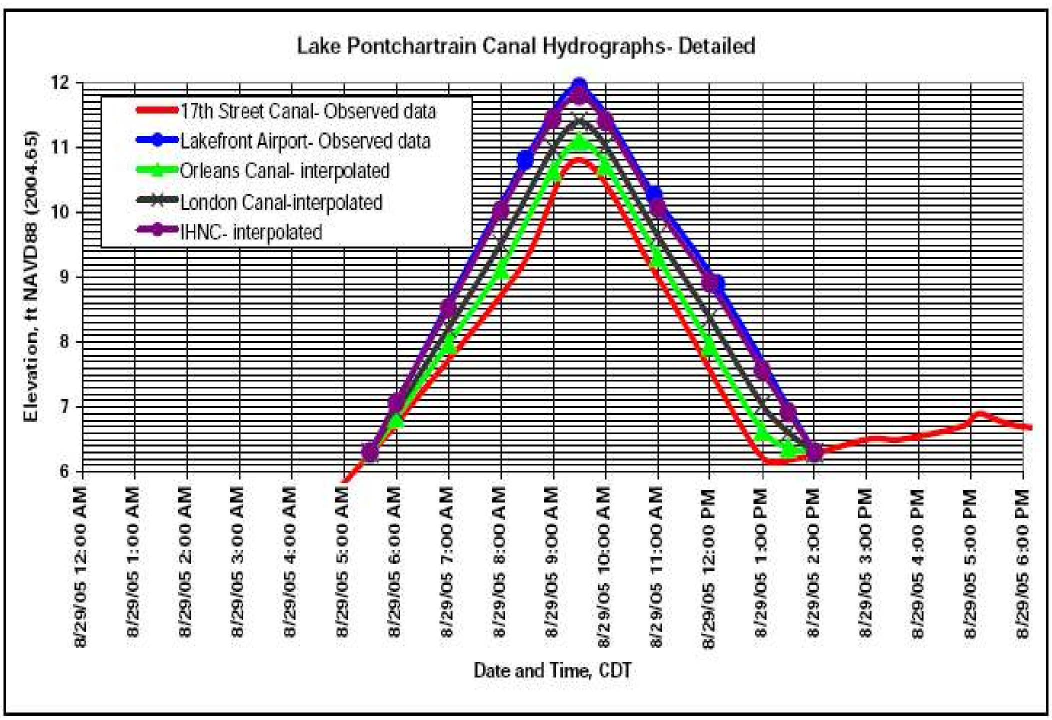

Figure 4.10 Constructed and Interpolated Hydrographs at Canal Entrances-Detailed View

Gage data defining the time variation of water level during Hurricane Katrina were not available on the south shore of Lake Pontchartrain in the vicinity of the breaches on 17th Street and London Canals or on the Inner Harbor Navigation Canal (IHNC). The time variation of water level is needed to define the water level at various events during the hurricane, such as the water level at the time of a floodwall breach. High water marks, intermediate water marks from photographs, and observations recorded in a log by an individual are used to construct a hydrograph for the 17th Street Canal. The resultant hydrograph for the 17th Street Canal is shown on Figure 4.11.

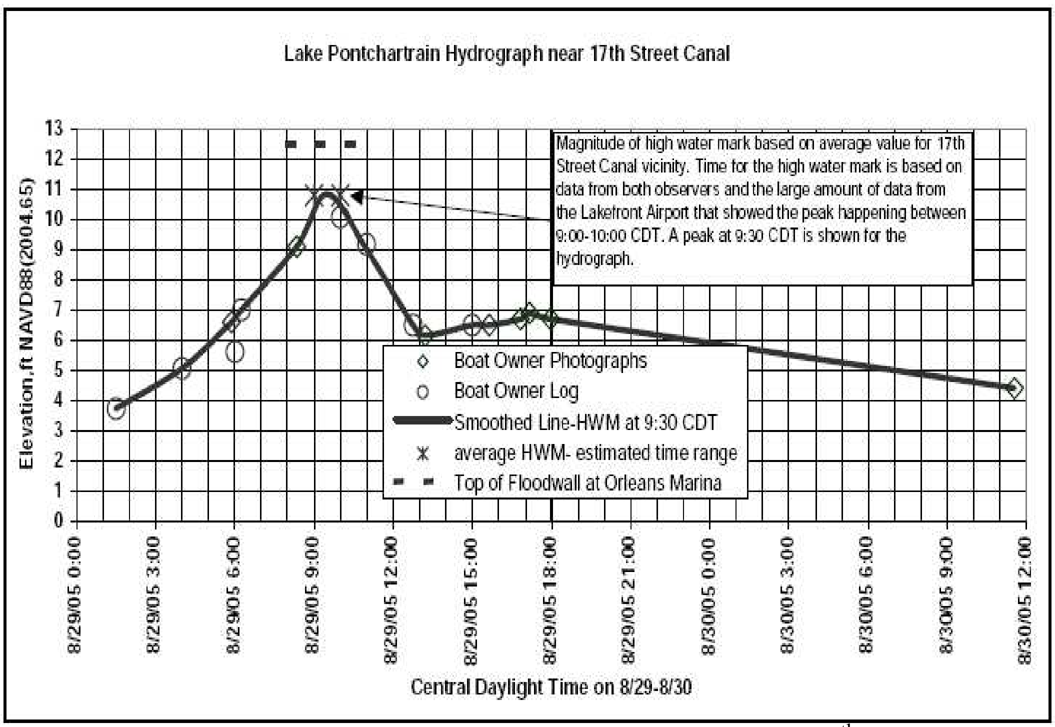

Figure 4.11 Constructed Hydrograph for Lake Pontchartrain at 17th Street Canal

Levee District personnel staying in the terminal building of the Lakefront Airport used digital cameras to record events during the passage of Hurricane Katrina on Monday August 29, 2005 including the rise and fall of storm surge both inside and outside the terminal building. The digital photographs were used to identify water level locations that were subsequently surveyed. The surveyed elevations along with the time stamp on the digital picture files were used to construct a hydrograph for the Airport location. The resultant hydrograph for the Lakefront Airport is shown on Figure 4.12.

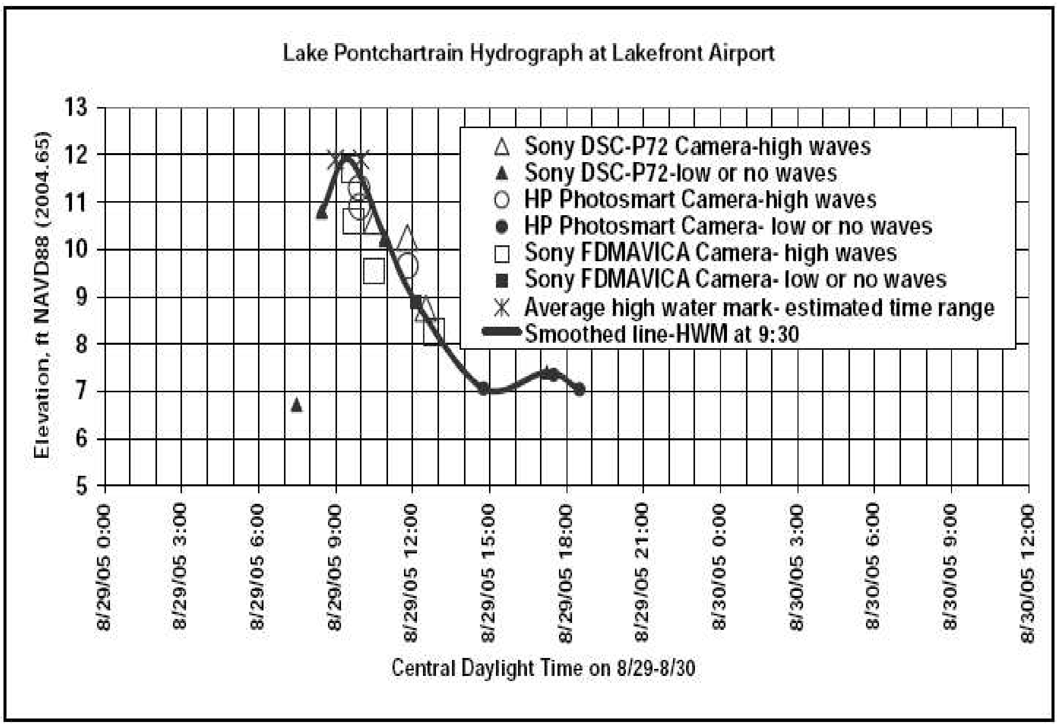

Figure 4.12 Constructed Hydrograph for Lake Pontchartrain at Lakefront Airport

The gauged hydrographs for the Midlake, Bayou Labranch, Pass Manchac, and Little Irish Bayou are shown in Figure 4.8. The interpolated hydrographs for the Orleans Avenue Canal and the London Avenue Canal are shown in both Figures 4.9 and 4.10. The constructed hydrographs for the 17^{th} Street Canal and the Lakefront Airport are shown in Figures 4.11 and 4.12 respectively. These are used to verify the reliability of the present model by comparing with the computed hydrographs for the 17^{th} Street Canal, the Orleans Avenue Canal, the London Avenue Canal, the Inner Harbor Navigation Canal (IHNC)-Lakefront Airport, Midlake, Bayou Labranch, Pass Manchac, and Little Irish Bayou. The detailed descriptions of the implementation of the present model and the comparison between the measured and the simulated hydrographs for studying the hurricane-induced oscillation in Lake Pontchartrain will be presented in the next section. The aerial photo showing the 17^{th} Street Canal (1), the Orleans Avenue Canal (2), the London Avenue Canal (3), the Inner Harbor Navigation Canal (so called IHNC,4), Midlake (5), Bayou Labranch (6), Pass Manchac (7), and Little Irish Bayou (8) is presented on Figure 4.13.

Figure 4.13 Aerial Photo Showing the 17th Street Canal (1), the Orleans Avenue Canal (2), the London Avenue Canal (3), IHNC (4), Midlake (5), Bayou Labranch (6), Pass Manchac (7), and Little Irish Bayou (8)

4.4 Verification of Numerical Model

The present model, named FVWATER, is used to study the oscillation in Lake Pontchartrain induced by wind generated by Hurricane Katrina. The dimensions of the uniform rectangular control-volumes (CV's) in a Cartesian grid are $(\Delta x, \Delta y) = (750\,m, 750\,m)$. The time-step Δt is chosen to be 45 seconds. The computational domain of Lake Pontchartrain used in the verification of the present model for this study is 60 km from west to east and 37.5 km from north to south and the approximate covering area of the computational domain corresponding to Lake

Pontchartrain and its surround swamps is 1475 km^2. The bathymetry of Lake Pontchartrain adopted from the Interagency Performance Evaluation Task Force (IPET) report is presented in Figure 4.14 and this bathymetry is exclusively used in all the numerical simulations made by the present model in this study.

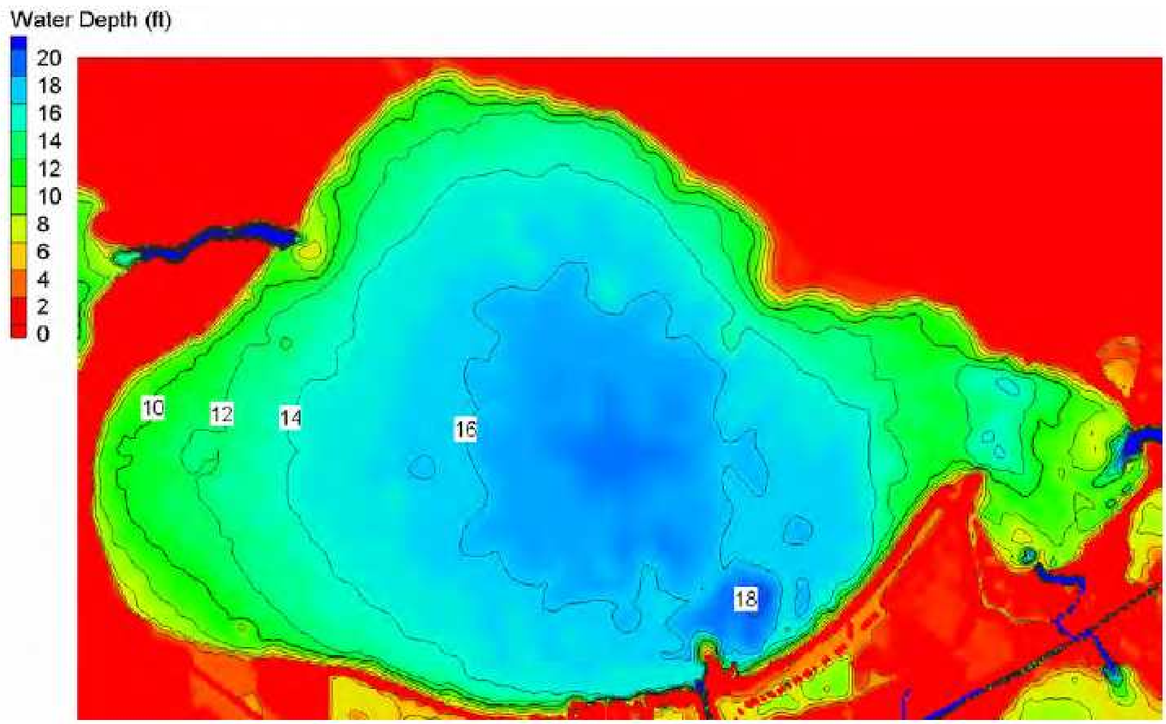

Figure 4.14 Lake Pontchartrain Bathymetry

The time-period in the verification processes for the present model is from 12:00 am UTC (Coordinated Universal Time) August 29, 2005 to 12:00 am UTC August 30, 2005, or 07:00 pm CDT (Central Daylight Time) August 28, 2005 to 07:00 pm CDT August 29, 2005. During this 24-hours time-period, Hurricane Katrina made two landfalls at Southeast Louisiana and the boarder of Louisiana/Mississippi, respectively, and passed by the region along the east shore of Lake Pontchartrain. Meanwhile, severe breaches of floodwalls along Mississippi River in Southeast Louisiana area and major flooding in the City of New Orleans and surround communities had happened within this 24-hours period. Hence, the study of the oscillation in Lake Pontchartrain induced by wind generated by Hurricane Katrina can be concentrated in this 24-hours period.

The wind field inducing the oscillations in Lake Pontchartrain is exclusively caused by Hurricane Katrina. The numerical typhoon (or hurricane) model named CLIMATE, based on Equation (3.9) through Equation (3.14) in Chapter 3, is developed along with the present model in this study. The meteorological data to simulate Hurricane Katrina between 12:00 am UTC August 29, 2005 and 12:00 am UTC August 30, 2005 are adopted from the Interagency Performance Evaluation Task Force (IPET) report and are listed in Table 4.1.

Table 4.1 Characteristics of Hurricane Katrina Required in Numerical Simulations

Date/Time (UTC)	**Central Pressure (bar)**	**Radius to Maximum Winds (m)**
Aug 29 0000	90400	26000
Aug 29 0300	90800	34000
Aug 29 0600	91000	34000
Aug 29 0900	91700	58000
Aug 29 1200	92300	67000
Aug 29 1500	93200	37000
Aug 29 1800	94800	30000
Aug 29 2100	95400	47000
Aug 30 0000	96300	34000

Miller and Thompson (1970) stated that the expansion of the eye of the hurricane is approximately to a time interval of less than an hour for the typical hurricane movement. In this study, it is reasonable to assume that the diameters of the eye of the simulated Hurricane Katrina by the numerical hurricane model (named CLIMATE) are the distances corresponding to a time interval of a half-hour traveling of Hurricane Katrina. The speeds for the simulated Hurricane Katrina derived from the moving path of Hurricane Katrina between 12:00 am UTC August 29, 2005 and 12:00 am UTC August 30, 2005 are interpreted from the hourly Latitudes and Longitudes of Hurricane Katrina recorded in the Interagency Performance Evaluation Task Force (IPET) report.

According to the Volume V, titled The Performance-Levees and Floodwalls, of the Interagency Performance Evaluation Task Force (IPET) report, there are several breaches of the floodwalls and levees on the 17th Street Canal, the London Avenue Canal, and the Inner Harbor Navigation Canal (IHNC) during the invasion of Hurricane Katrina. The diagram showing the locations of these breaches adopted from the IPET report is presented on Figure 4.15. From Figure 4.15, it can be seen that these breaches are not within the current computational domain of Lake Pontchartrain. In order to accommodate the phenomena of both breaches and/or overtopping of floodwalls and levees along Lake Pontchartrain, the water flows out of Lake Pontchartrain through the entrances of the 17th Street Canal, the London Avenue Canal, and the Inner Harbor Navigation Canal (IHNC) at the 15th hour (or 03:00 pm UTC August 29) of the numerical simulations performed for the model verification.

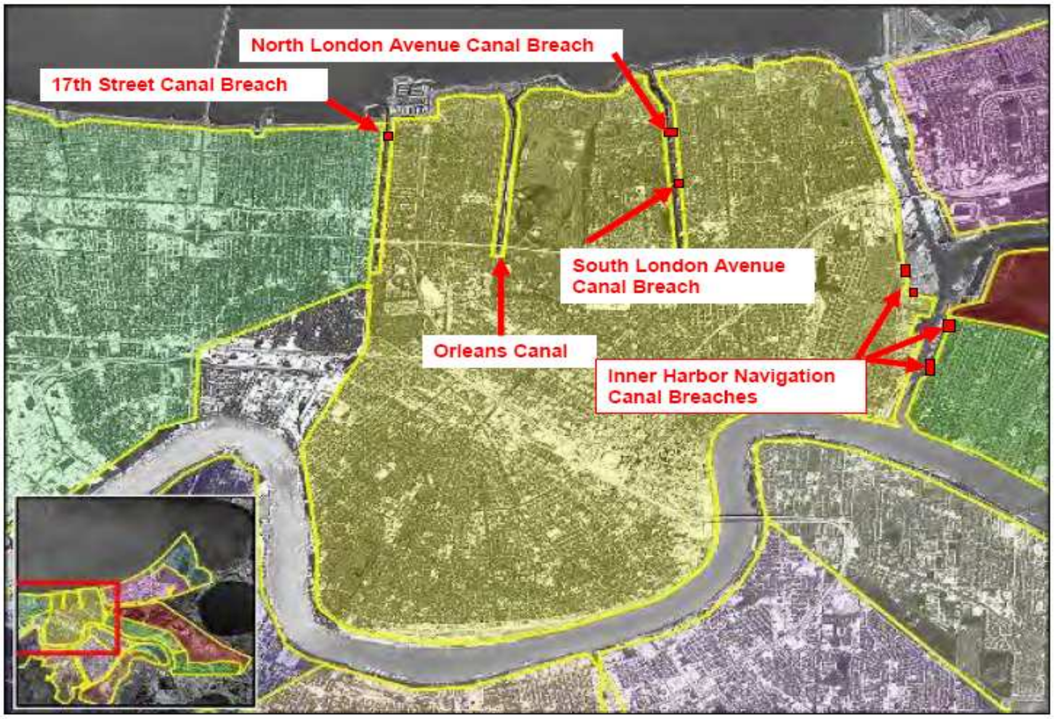

Figure 4.15 Locations of Major Breaches within South Shore of Lake Pontchartrain

The computed hydrograph (solid black line) obtained from the present model and the observed hydrograph (red line with star symbol) at the entrance of the 17th Street Canal are presented on Figure 4.16. From Figure 4.16, it is seen that the present model-computed time when the peak water surface elevation (WSE, so called water level in the IPET report) happens is almost identical to the observed-time at which the maximum water level happened at the entrance of the 17th Street Canal site. Besides, the difference of the maximum water level (water surface elevation, WSE) is approximately 0.01 meter (3.30 m versus 3.29 m). It shows that the present model can correctly predict the general trend of the rise and fall of the water level at the entrance of the 17th Street Canal site.

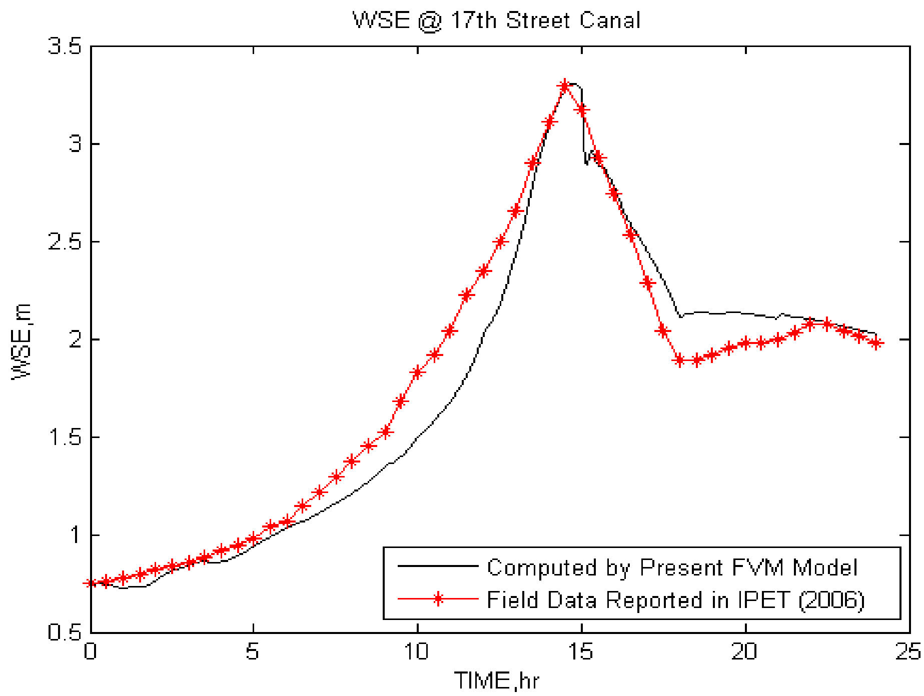

Figure 4.16 Computed Hydrograph versus Observed Hydrograph, 17^{th} Street Canal

The computed hydrograph (solid black line) obtained from the present model and the constructed hydrograph (green line with cross symbol) for the entrance of the Orleans Avenue Canal are presented on Figure 4.17. It should be mentioned that there is no water flowing out of Lake Pontchartrain through this location because there is no breach or overtopping of the floodwalls and levees on the Orleans Avenue Canal during the invasion of Hurricane Katrina. Here, it is seen that the present model-predicted time when the peak water level happens is almost identical to the observed-time at which the maximum water level happened at the entrance of the Orleans Avenue Canal site. Besides, the difference of the maximum water level (water surface elevation, WSE) is approximately 0.11 meter (3.27 m versus 3.38 m). It shows that the present model can correctly predict the general trend of the rise and fall of the water level when the hydrograph due to Hurricane Katrina is compared with the constructed hydrograph for the entrance of the Orleans Avenue Canal site.

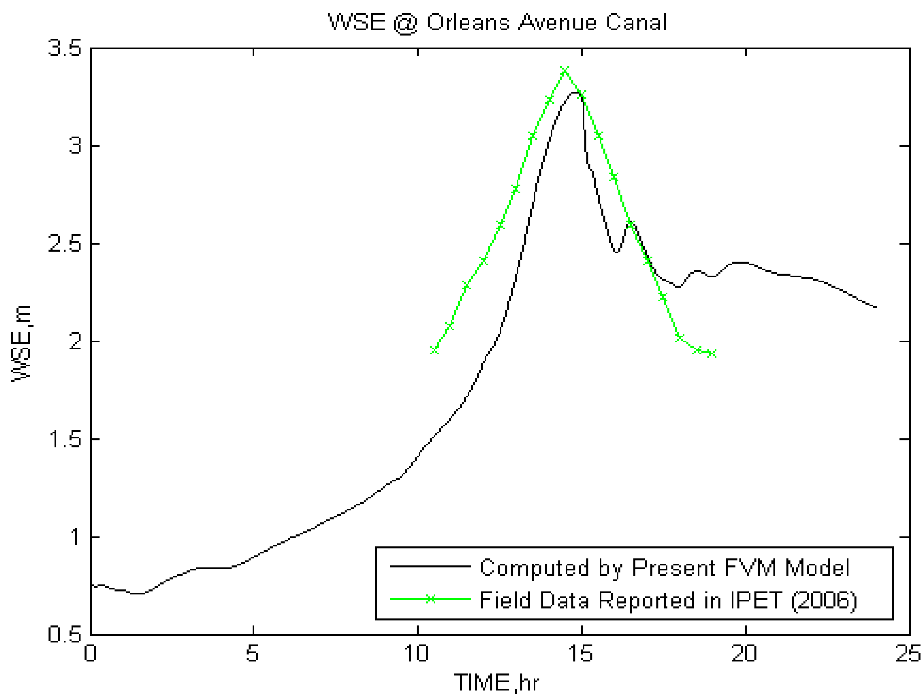

Figure 4.17 Computed Hydrograph versus Interpolated Hydrograph, Orleans Avenue Canal

The computed hydrograph (solid black line) obtained from the present model and the constructed hydrograph (purple line with plus symbol) for the entrance of the London Avenue Canal are presented on Figure 4.18. Here, it is seen that the present model-predicted time when the peak water level happens is almost identical to with the observed-time at which the maximum water level happened at the entrance of the London Avenue Canal site. Although the difference of the maximum water level (water surface elevation, WSE) is approximately 0.18 meter (3.30 m versus 3.48 m), it can still be claimed that the present model can correctly predict the general trend of the rise and fall of the water level when the hydrograph due to Hurricane Katrina is compared with the constructed hydrograph for the entrance of the London Avenue Canal site.

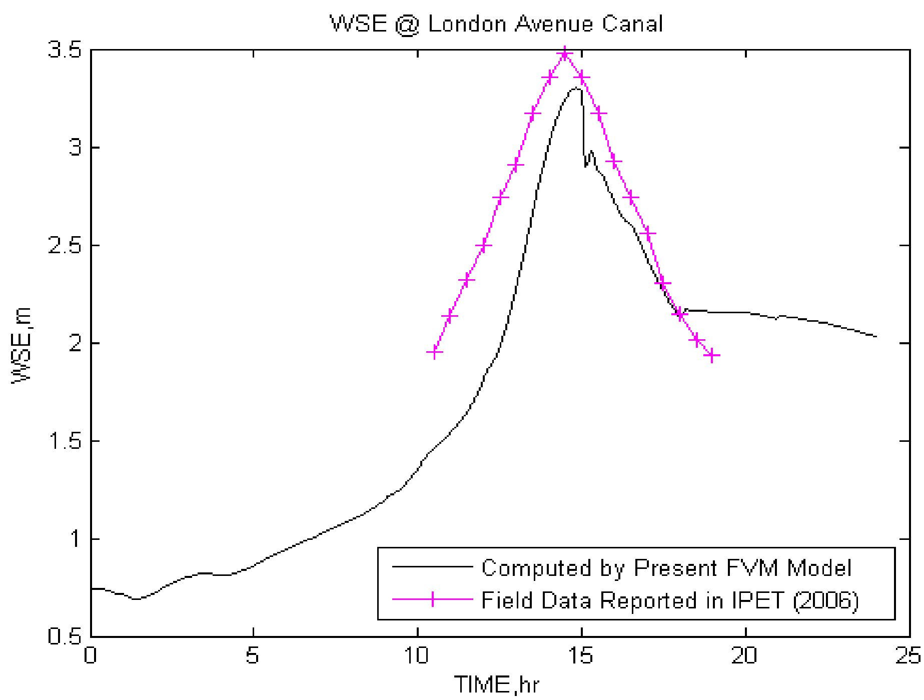

Figure 4.18 Computed Hydrograph versus Interpolated Hydrograph, London Avenue Canal

The computed hydrograph (solid black line) obtained from the present model and the observed hydrograph (blue line with circle symbol) for the IHNC-Lakefront Airport are presented on Figure 4.19. Here, it is seen that the present model-predicted time when the peak water level happens is almost identical to the observed-time at which the maximum water level happened at the IHNC-Lakefront Airport site. Although the difference of the maximum water level (water surface elevation, WSE) is approximately 0.36 meter (3.30 m versus 3.66 m), it can still be claimed that the present model can correctly predict the general trend of the rise and fall of the water level when the hydrograph due to Hurricane Katrina is compared with the observed hydrograph at the IHNC-Lakefront Airport site.

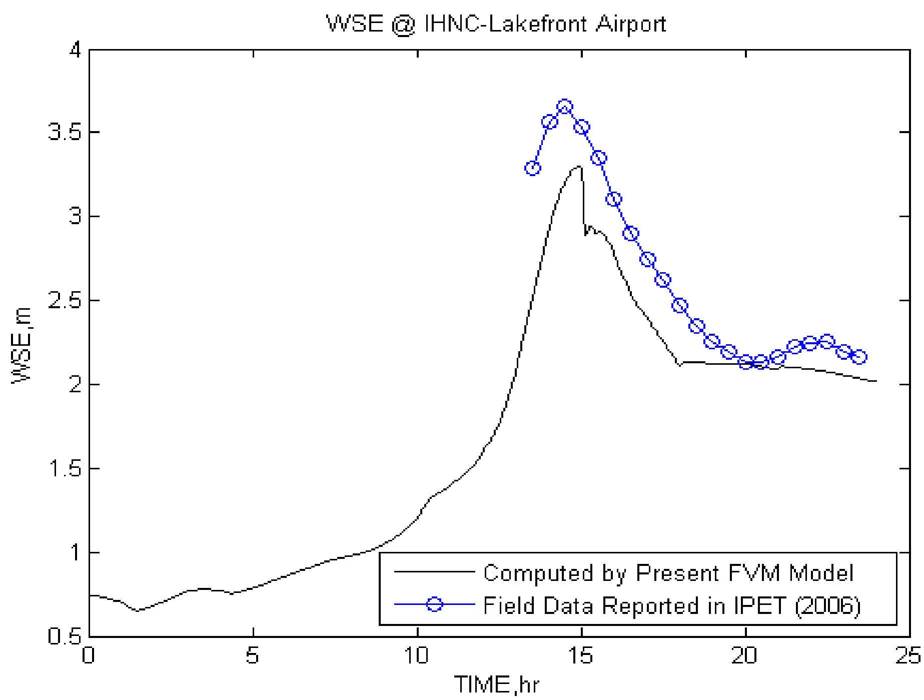

Figure 4.19 Computed Hydrograph versus Observed Hydrograph, IHNC-Lakefront Airport

The computed hydrograph (solid black line) obtained from the present model and the observed hydrograph (light blue line with cross symbol) for the Midlake are presented on Figure 4.20. According to the IPET report, the Midlake gage stopped operating in the middle of the storm; hence, the comparison of the computed and the observed hydrographs can be focused on the times at which the Midlake gage data is still available between 12:00 am August 29 and 12:00 am August 30 2005. From Figure 4.20, it shows that the present model can correctly predict the general trend of the rise of the water level prior to the stop-recording of the Midlake gage when the hydrograph due to Hurricane Katrina is compared with the observed hydrograph at the Midlake site.

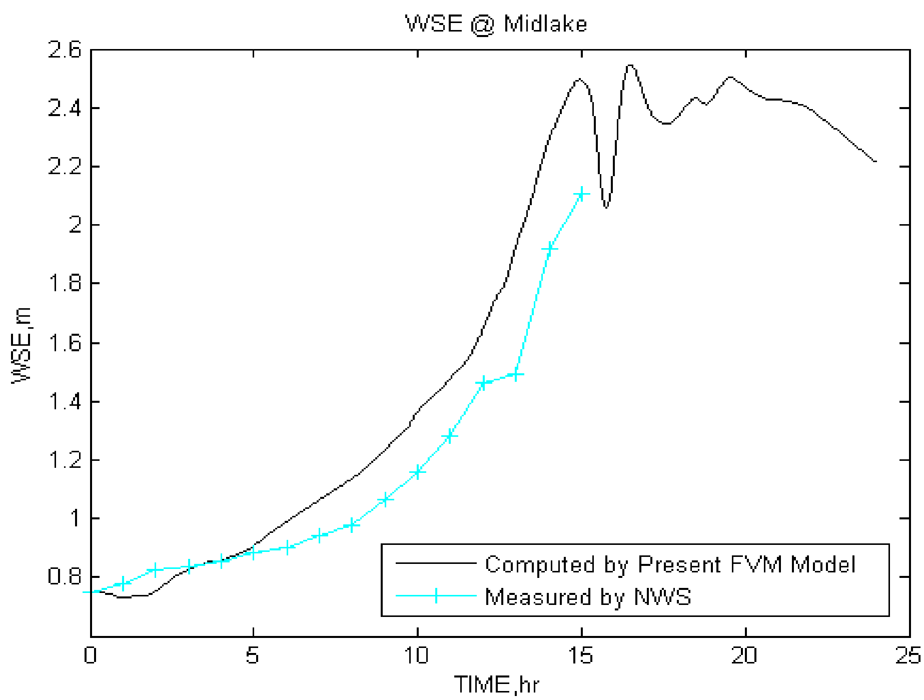

Figure 4.20 Computed Hydrograph versus Observed Hydrograph, Midlake

The computed hydrograph (solid black line) obtained from the present model and the observed hydrograph (purple line with cross symbol) for Bayou La Branche (named Bayou Labranch in the IPET report) are presented on Figure 4.21. It can be seen from Figures 4.7 and 4.13 that the location of the Bayou Labranch gage is in the swamp along the southwest shore of Lake Pontchartrain. In detail, the swamps along the entire southwest shore of Lake Pontchatrain have been assigned into the computational domain for the current numerical simulations performed by the present model. From Figure 4.21, it can be claimed that the general trend of the rise and fall of the water level predicted by the present model is still reasonable when it is compared with the observed hydrograph at Bayou Labranch site although the differences of the magnitudes between the simulated and the observed hydrographs are evident. According to IPET, it is possible that the readings of the Bayou Labranch gage are affected by the fact that the Bayou Labranch gage (NOAA Station ID: 8762372) is connected to Lake Pontchartrain by a channel which is about 0.5 mile along. Therefore, the low water surface elevations recorded by the gage are due to the geographic characteristics of the gage location. Furthermore, IPET demonstrates that the probable peak water surface elevation (WSE) at Bayou Labranch is between 7.75 ft and 8 ft (between 2.35 m and 2.45 m, the blue cross on Figure 4.22) based on the observed high water marks (HWMs) at Frenier and Williams Boulevard (see Figures 4.7 and 4.22, the red line on Figure 4.22). In order to visualize this statement presented by IPET, the computed hydrograph (solid black line) obtained from the present model and the adjusted hydrograph (purple line with cross symbol) according to the geographic characteristic of the Bayou La Branche gage are presented on Figure 4.23. It can be seen from Figure 4.23 that the difference between the predicted peak water surface elevation (WSE) by the present model and the best estimated peak water level by IPET presented by the adjusted hydrograph will be less than 0.6 m (or 23%); in other words, the present model can predict reasonable water surface elevations (WSEs) at Bayou La Branche site.

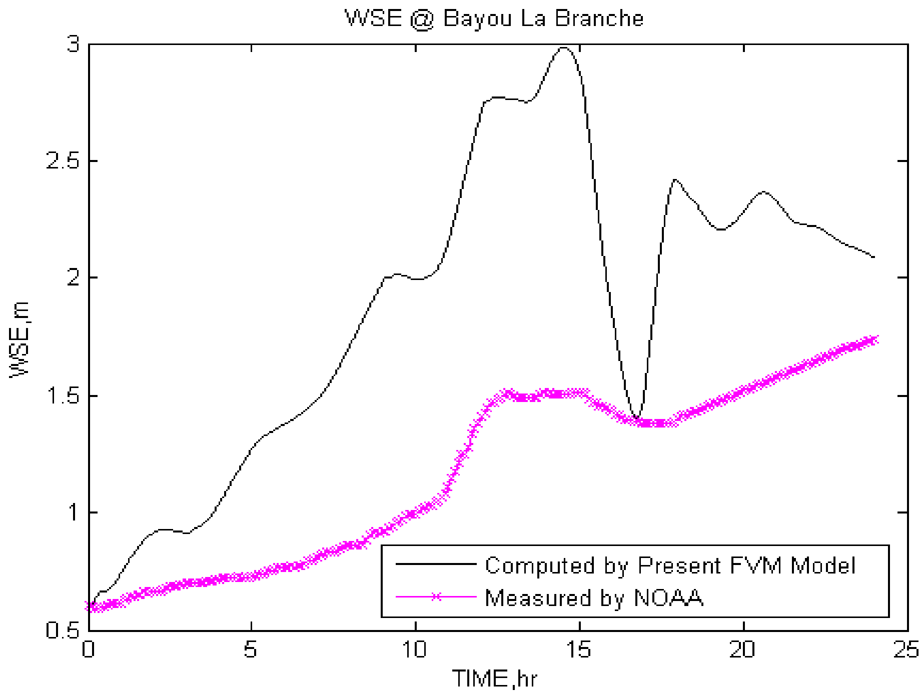

Figure 4.21 Computed Hydrograph versus Observed Hydrograph, Bayou Labranch

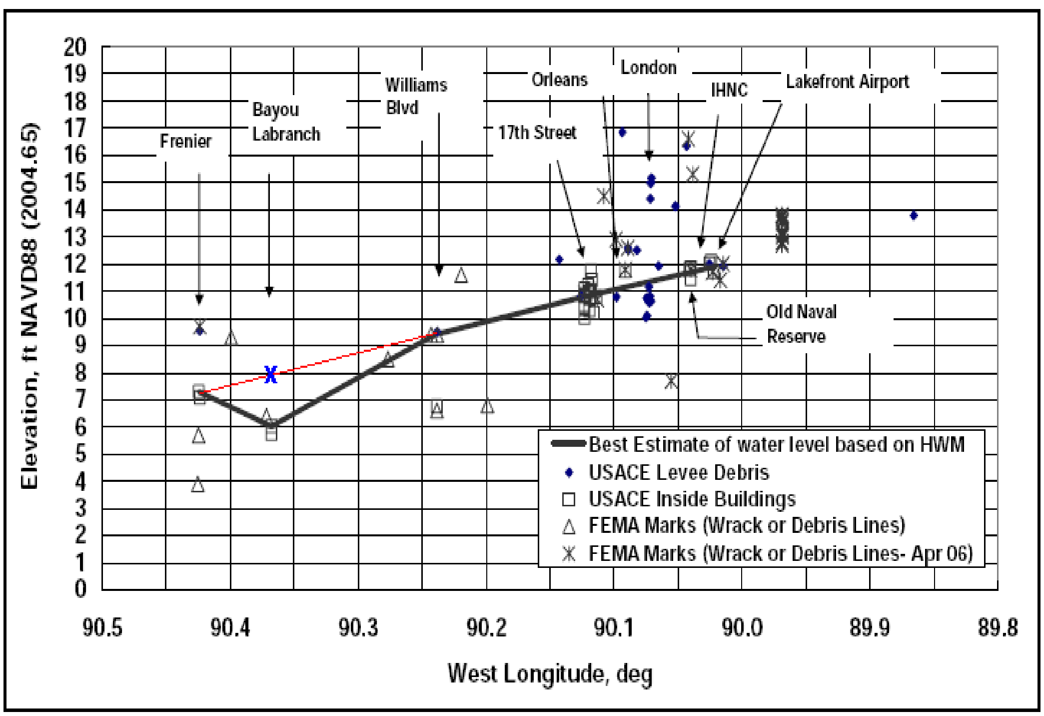

Figure 4.22 Estimation of Peak Water Level at Bayou Labranch Proposed by IPET

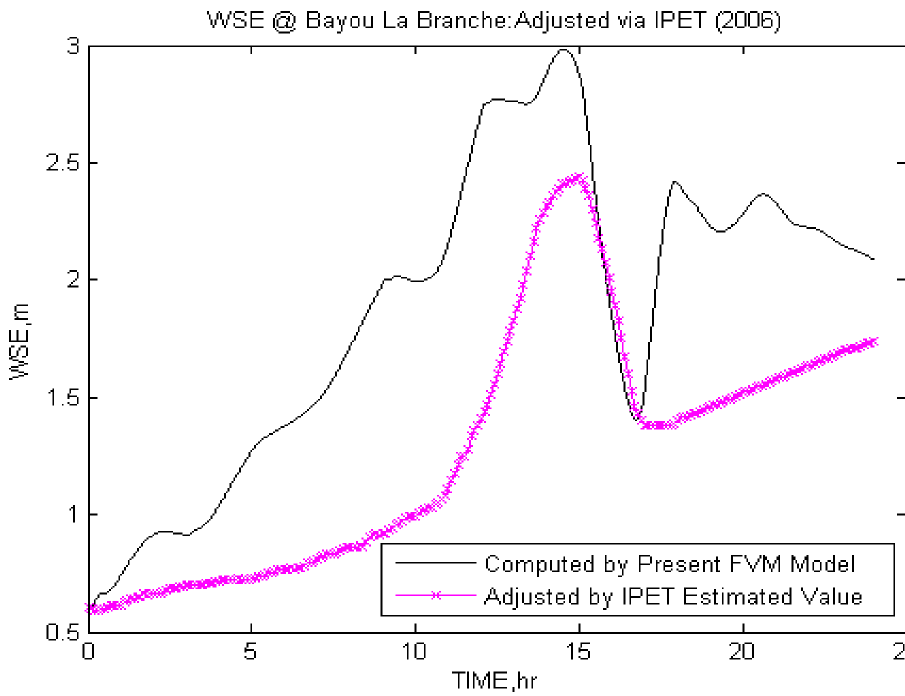

Figure 4.23 Computed Hydrograph versus Adjusted Observed Hydrograph, Bayou Labranch

The computed hydrograph (solid black line) obtained from the present model and the observed hydrograph (light blue line with circle symbol) for Pass Manchac are presented on Figure 4.24. From Figures 4.7 and 4.13, it can be seen that the location of the Pass Manchac gage (USGS ID No: 301748090200900, named Turtle Cove Environmental Research Station) is close to the middle of Pass Manchac, the narrow strip of water connecting Lake Pontchartrain and Lake Maurepas, on the northwest shore of Lake Pontchartrain. From Figure 4.24, it can be claimed that the general trend of the rise and fall of the water level predicted by the present model is still reasonable when it is compared with the observed hydrograph at the Pass Manchac-Turtle Cove site although the differences of the magnitudes between the simulated and the observed hydrographs are evident. It is possible that these differences are caused by the fact that the detailed geographical and/or hydraulic conditions affecting the operating the USGS Pass Manchac-Turtle Cove gage are not applied into the numerical simulations for the present study.

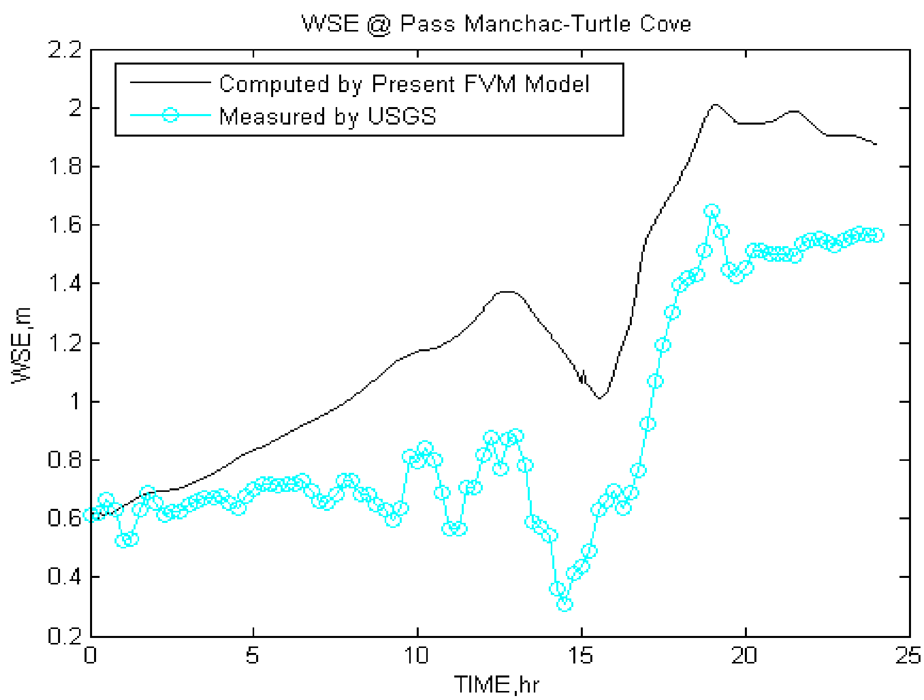

Figure 4.24 Computed Hydrograph versus Observed Hydrograph, Pass Manchac-Turtle Cove

In order to verify the accuracy of the present model predicting the water surface elevations (WSEs) on Pass Manchac, the water levels recorded by Pass Manchac gage (USACE ID No: 85420) at Manchac have been obtained. The location of USACE Pass Manchac gage (85420) is shown on Figure 4.25 and the computed hydrograph (solid black line) obtained from the present model and the observed hydrograph (red line with cross-mark) for USACE Pass Manchac gage are presented on Figure 4.26. According to the New Orleans District of USACE, the Pass Manchac gage failed in the middle of the storm; hence, the comparison of the computed and the observed hydrographs can be focused on the hours when the Pass Manchac gage is still operating. From Figure 4.26, it shows that the present model can correctly predict the general trend of the rise of the water level prior to the failure of the Pass Manchac gage when the hydrograph due to Hurricane Katrina is compared with the observed hydrograph at the west end of Pass Manchac.

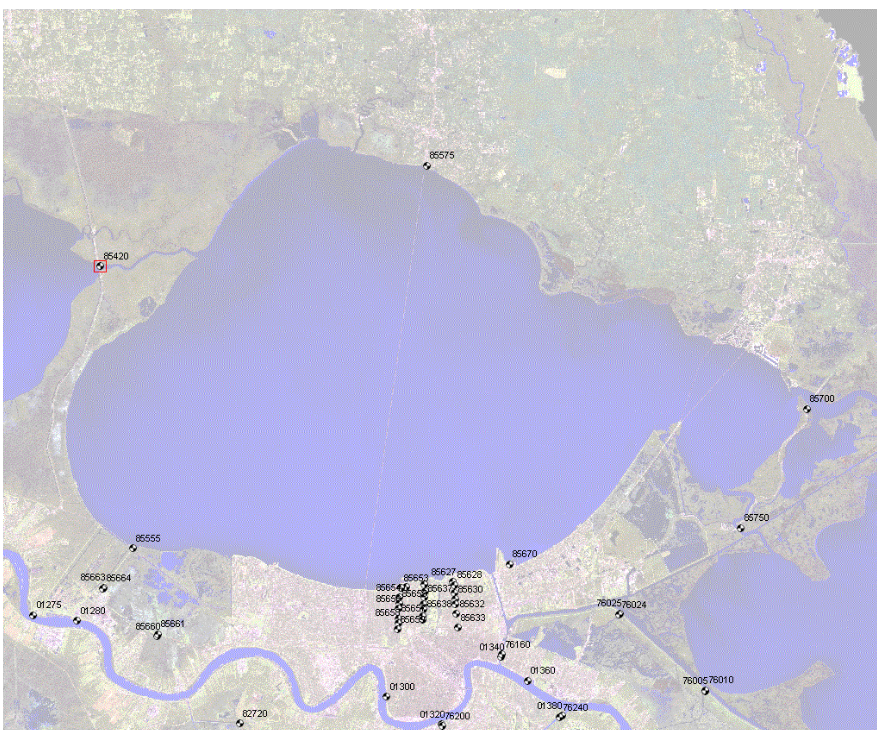

Figure 4.25 Map showing USACE Pass Manchac Gage (ID No: 85420) at Manchac (provided by USACE New Orleans District)

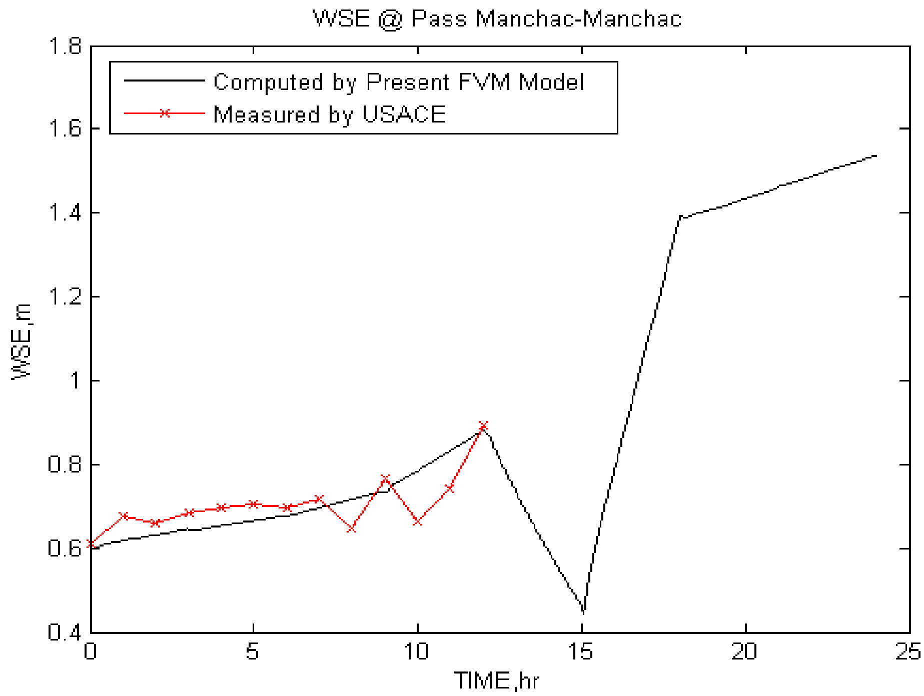

Figure 4.26 Computed Hydrograph versus Observed Hydrograph, Pass Manchac-Manchac

The computed hydrograph (solid black line) obtained from the present model and the observed hydrograph (green line with circle symbol) for Little Irish Bayou are presented on Figure 4.27. According to the IPET report, the Little Irish Bayou gage failed before high water levels were reached; hence, the comparison of the computed and the observed hydrographs can be focus on the times at which the Little Irish Bayou gage data is available. From Figure 4.27, it is seen that the general trend of the rise and fall of the water level predicted by the present model is not very closed to the general trend of the rise and fall of the water level because the present model does not include the intruding water from the Gulf of Mexico through the swamps along the east shore of Lake Pontchartrain. In detail, the present model can correctly predict the general trend of the rise of the water level between 09:00 am and 02:00 pm UTC August 29, 2005 as it is seen from Figure 4.27; however, the obvious differences between the computed and observed hydrographs can be seen when the computed hydrograph obtained from the present model is compared with the observed hydrograph between 12:00 and 09:00 am at Little Irish Bayou site. Based on the observational information provided in the IPET report, the low-land areas between Lake Pontchartrain and the Gulf of Mexico have been inundated by the storm surges induced by Hurricane Katrina before the start (12:00 am UTC August 29, 2005) of the current computational simulation. In other words, the storm surges from the Gulf of Mexico had been affecting the rise and fall of the water level at the east part of Lake Pontchartrain, at which the Little Irish Bayou gage is located, since Hurricane Katrina was approaching to the Southeast Louisiana. It can be still claimed that the present model can reasonably predict the general trend of the water level at Little Irish Bayou site.

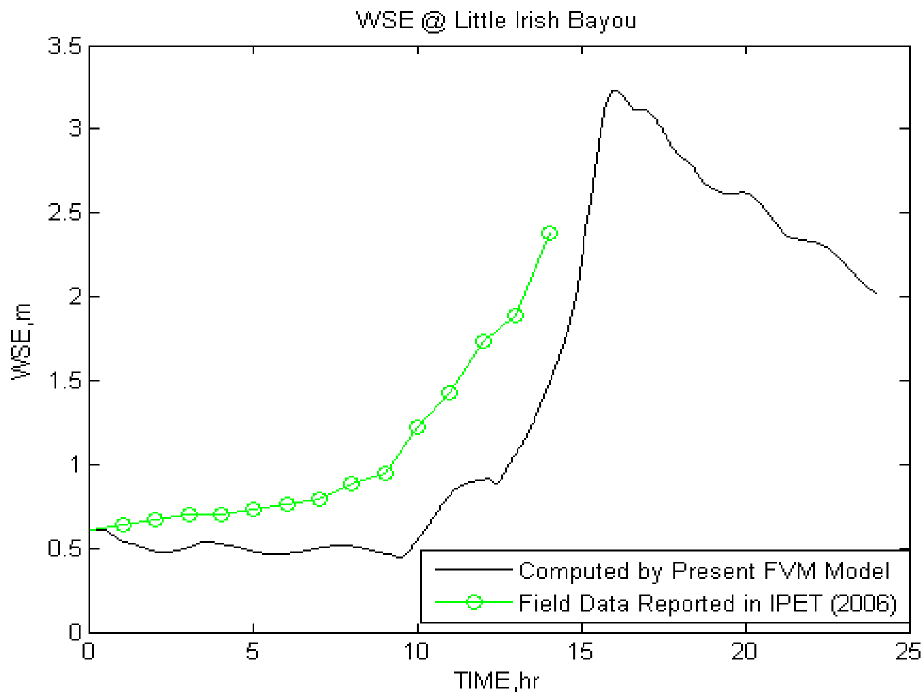

Figure 4.27 Computed Hydrograph versus Observed Hydrograph, Little Irish Bayou

It is evident that the time at which the maximum water surface elevation (WSE) occurs as predicted by the present model is almost identical to the time at which the maximum water level is observed at the 17th Street Canal, the Orleans Avenue Canal, the London Avenue Canal, and IHNC-Lakefront Airport sites. The differences between the computed and the observed maximum WSE at these four sites are within the range of 0.01 to 0.36 meter (or 0.3% ~ 10%) from Figures 4.16 to 4.19. Furthermore, the present model can correctly predict the general trend of the water level when the hydrographs due to Hurricane Katrina are compared with the observed hydrographs at the 17th Street Canal, the Orleans Avenue Canal, the London Avenue Canal, the IHNC-Lakefront Airport, and the Midlake sites from Figures 4.16 to 4.20. Because the detailed hydraulics influencing the Bayou La Branche (named Bayou Labranch by IPET) gage and the geographic complexities affecting the operations of the Pass Manchac-Turtle Cove gage are not included into the current numerical simulations, the general trends of the water level predicted by the present model are not correct when the hydrographs due to Hurricane Katrina are compared with the observed hydrographs at these two sites from Figures 4.21, 4.23, and 4.24. Because the storm surges intruding from Gulf of Mexico through the swamps along the east shores of Lake Pontchatrain are not included in the present model, the general trend of the water level predicted by the present model is not correct when the hydrograph due to Hurricane Katrina is compared with the observed hydrograph at Little Irish Bayou site from Figure 4.27.

Because the general trends of water levels either are correctly predicted at the 17th Street Canal, the Orleans Avenue Canal, the London Avenue Canal, the IHNC-Lakefront Airport, the Midlake, and the Pass Manchac-Manchac sites and are reasonably predicted at the Bayou La Branche, Pass Manchac-Turtle Cove, and the Little Irish Bayou sites by the present model when the hydrographs due to Hurricane Katrina are compared with the constructed/observed hydrographs at these sites, it is confident to claim that the present model for solving the depth-averaged, non-linear shallow water equations (NLSW) is a reliable numerical model to study the oscillations of semi-enclosed water body induced by hurricanes even though the present model can not correctly predict the general trends of the water levels when the hydrographs due to Hurricane Katrina are compared with the available observed hydrographs at Bayou La Branche, Pass Manchac-Turtle Cove, and

Little Irish Bayou sites. Furthermore, the present model will be used in several detailed studies of the oscillations (storm surges) in Lake Pontchartrain induced by winds generated through Hurricane Katrina and other simulated hurricanes.

4.5 Applications of Numerical Model

After the validity of the present model for solving the depth-averaged, non-linear shallow water equations (NLSW) has been affirmed, the present model is applied to study the wind-induced oscillations in Lake Pontchartrain generated by four (4) different synthetic hurricanes:

1. Original Hurricane Katrina (Route 1 shown in Figure 4.28).
2. Hurricane Katrina passing above east part of New Orleans, Louisiana (Route 2 shown in Figure 4.28).
3. Hurricane Katrina passing through the regions along the west shore of Lake Pontchartrain, including Lake Maurepas (Route 3 shown in Figure 4.28).
4. A simulated hurricane traveling the same route as Hurricane Katrina with reduced forward speeds (Route 1 shown in Figure 4.28).

In order to examine the oscillations in Lake Pontchartrain induced by wind generated through these hurricanes in detail, including original Hurricane Katrina, two cross sections (South-North (S-N) and West-East (W-E)) of Lake Pontchartrain are drawn and the reference WSE (η) is adjusted to zero. The map showing the locations of both cross sections of Lake Pontchartrain is presented on Figure 4.29. The computed hydrographs of both S-N and W-E cross sections and the computed contour maps of the entire Lake Pontchartrain are used to present the oscillation phenomena in Lake Pontchartrain induced by winds generated through these four (4) hurricanes. The discussions of these hydrographs and contours maps showing the wind-induced oscillations in Lake Pontchartrain generated by the present model are presented in the following sub-sections.

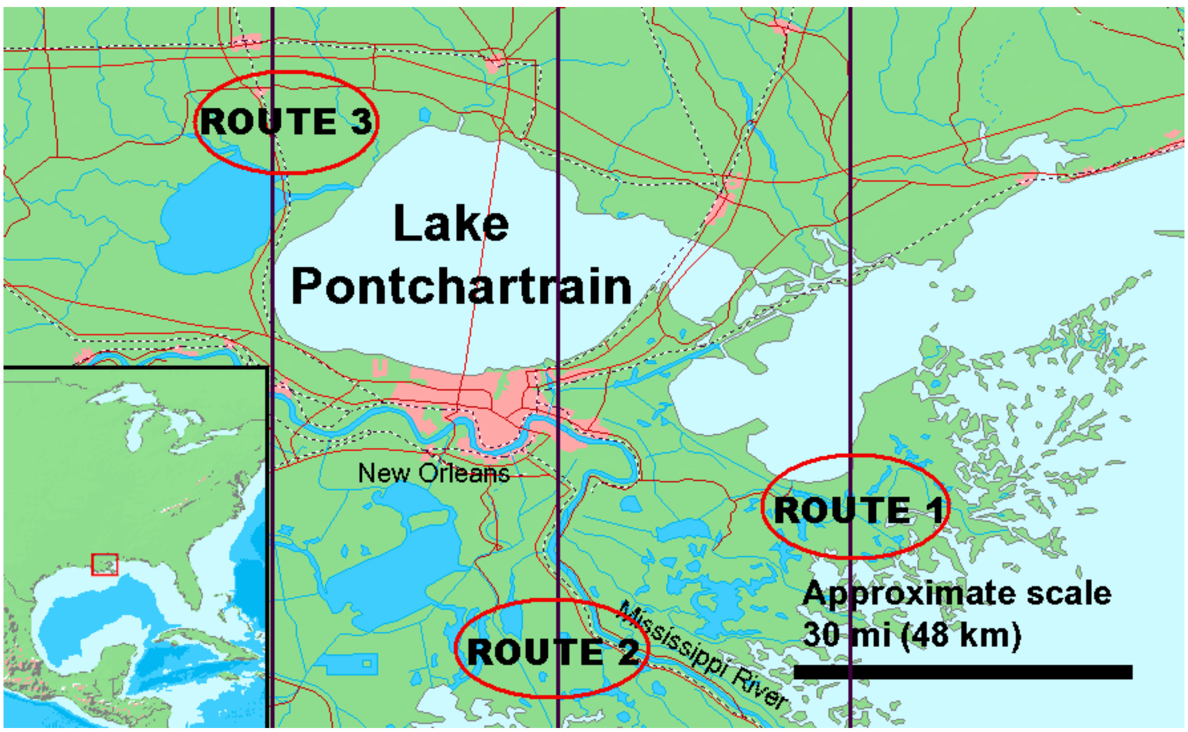

Figure 4.28 Map Showing Different Routes of Hurricanes

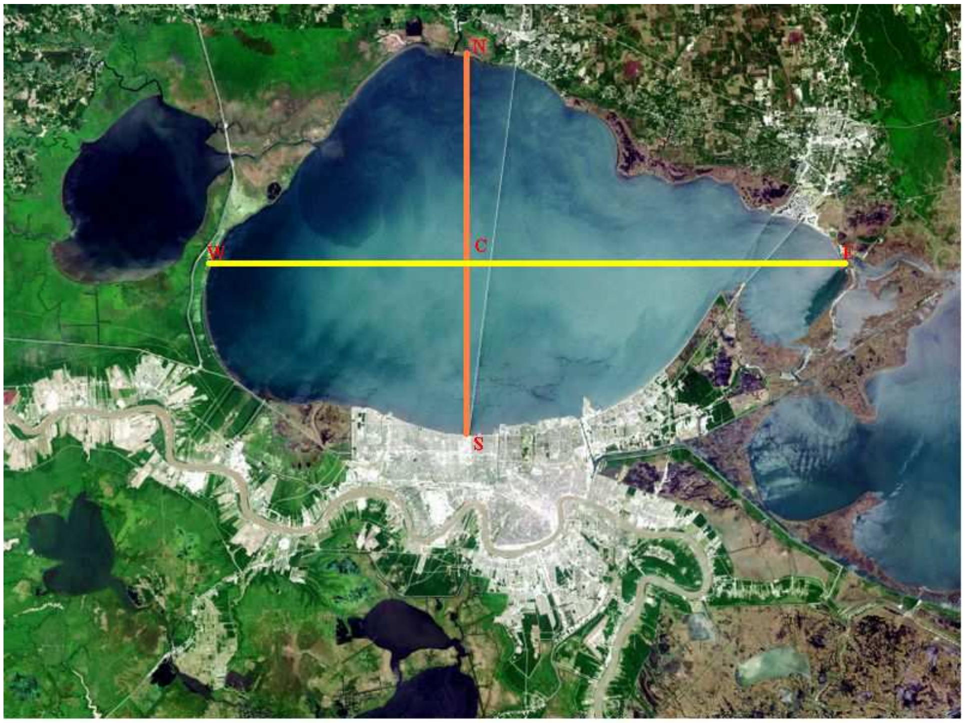

Figure 4.29 Approximate Locations of S-N and W-E cross-sections

4.5.1 Original Hurricane Katrina (Route 1)

The present model is used to study the oscillation in Lake Pontchartrain induced by wind generated by the Route 1-traveling Hurricane Katrina (see Figure 4.28). The dimensions of the uniform rectangular control-volumes (CV's) in a Cartesian grid are $(\Delta x, \Delta y) = (750\,m, 750\,m)$. The time-step Δt is chosen to be 45 seconds. The bathymetry of Lake Pontchartrain adopted from the Interagency Performance Evaluation Task Force (IPET) report is used in the numerical simulations (see Figure 4.14). The time-period in the numerical simulations for the oscillation in Lake Pontchartrain induced by wind generated by the Route 2-traveling Hurricane Katrina is from 12:00 am UTC

(Coordinated Universal Time) August 29, 2005 to 12:00 am UTC August 30, 2005, or 07:00 pm CDT (Central Daylight Time) August 28, 2005 to 07:00 pm CDT August 29, 2005. During this 24-hours time-period, Hurricane Katrina made two landfalls at Southeast Louisiana and the boarder of Louisiana/Mississippi, respectively, and passed by the region along the east shore of Lake Pontchartrain (see Figures 4.2 and 4.28). Hence, the study of the oscillation in Lake Pontchartrain induced by wind generated by the Route 1-traveling Hurricane Katrina can be concentrated in this 24-hours period. In order to study the oscillation phenomena in Lake Pontchartrain induced by the Route-1 traveling Hurricane Katrina, the breaches and/or overtopping of floodwalls and levees along Lake Pontchartrain will not be accommodated into the numerical simulations performed by the present model for this case; hence, the water can not flow out of the lake through the entrances of the canals connecting to the lake during the entire 24-hours period of the numerical simulations for the oscillations of Lake Pontchartrain induced by the Route-1 traveling Hurricane Katrina.

The wind field inducing the oscillations in Lake Pontchartrain is exclusively caused by the Route 1-traveling Hurricane Katrina. The numerical typhoon (or hurricane) model, based on Equation (3.9) through Equation (3.14) in Chapter 3 and developed along with the present model in this study, is used to generate the pressure and wind fields. The meteorological data to simulate Hurricane Katrina between 12:00 am UTC August 29, 2005 and 12:00 am UTC August 30, 2005 are adopted from the Interagency Performance Evaluation Task Force (IPET) report and are listed in Table 4.1. The diameters of the eye of the simulated Hurricane Katrina by the numerical hurricane model are the distances corresponding to a time interval of a half-hour traveling of the simulated Hurricane Katrina. The speeds for the simulated Hurricane Katrina derived from the moving path of Hurricane Katrina between 12:00 am UTC August 29, 2005 and 12:00 am UTC August 30, 2005 are interpreted from the hourly Latitudes and Longitudes of Hurricane Katrina recorded in the Interagency Performance Evaluation Task Force (IPET) report.

The computed hydrograph (solid black line) obtained from the present model for the 17th Street Canal is presented on Figure 4.30. From Figure 4.30, it is seen that the peak water surface elevation (WSE, so called water level in the IPET report) computed by the present model is approximately 3.30 m at the 17th Street Canal site. In detail, the water surface elevations induced by the Route 1-traveling Hurricane Katrina are identical to the water surface levels induced by the original Hurricane Katrina at the 17th Street Canal site until the 15th hour of the numerical simulations (see the solid red line on Figure 4.30). Due to the absence of the breaches and/or overtopping of floodwalls and levees along Lake Pontchartrain, the residual water surface elevations for the Route 1-traveling Hurricane Katrina are much higher than the ones for the original Hurricane Katrina after the 15th hour of the numerical simulations. Hence, this is an evidential proof that the tremendous amount of water escaping from Lake Pontchartrain through the breaches and/or overtopping of floodwalls and levees can bring a devastating damage to the communities surrounding Lake Pontchartrain.

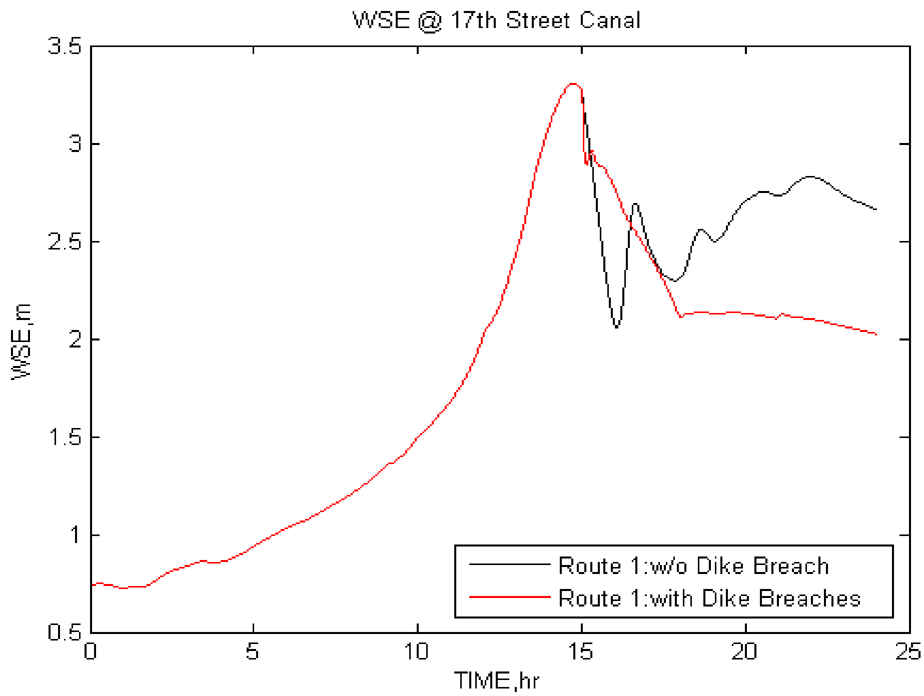

Figure 4.30 Computed Hydrograph, 17th Street Canal

The computed hydrograph (solid black line) obtained from the present model for the Orleans Avenue Canal is presented on Figure 4.31. From Figure 4.31, it is seen that the peak water surface elevation (WSE, so called water level in the IPET report) computed by the present model is approximately 3.27 m at the Orleans Avenue Canal site. In detail, the water surface elevations induced by the Route 1-traveling Hurricane Katrina are identical to the water surface levels induced by the original Hurricane Katrina at the Orleans Avenue Canal site until the 15th hour of the numerical simulations (see the solid red line on Figure 4.31). Due to the absence of the breaches and/or overtopping of floodwalls and levees along Lake Pontchartrain, the residual water surface elevations for the Route 1-traveling Hurricane Katrina are much higher than the ones for the original

Hurricane Katrina after the 15th hour of the numerical simulations. Hence, this is an evidential proof that the tremendous amount of water escaping from Lake Pontchartrain through the breaches and/or overtopping of floodwalls and levees can bring a devastating damage to the communities surrounding Lake Pontchartrain.

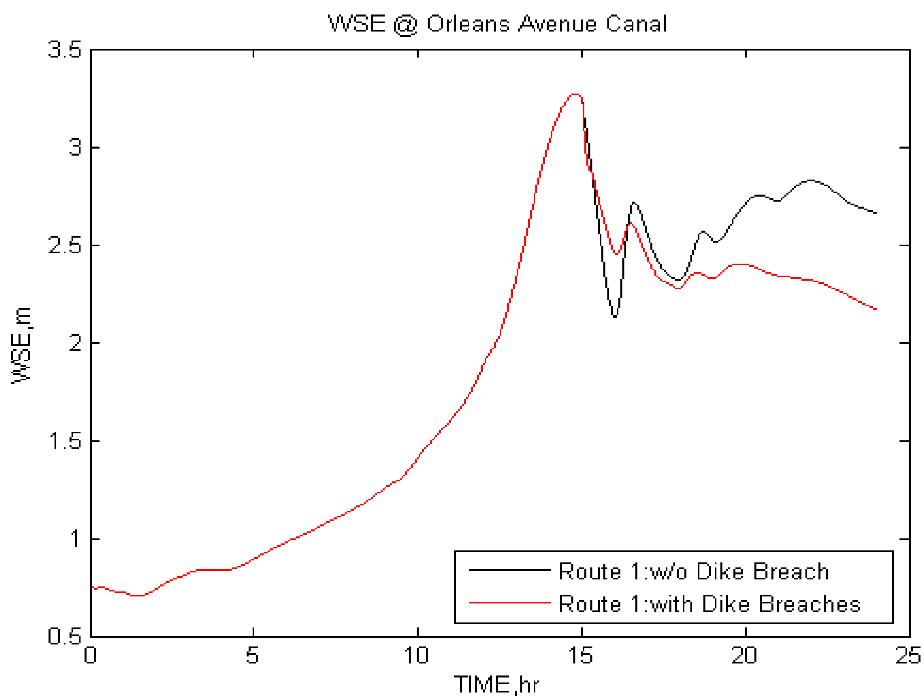

Figure 4.31 Computed Hydrograph, Orleans Avenue Canal

The computed hydrograph (solid black line) obtained from the present model for the London Avenue Canal is presented on Figure 4.32. From Figure 4.32, it is seen that the peak water surface elevation (WSE, so called water level in the IPET report) computed by the present model is approximately 3.30 m at the London Avenue Canal site. In detail, the water surface elevations induced by the Route 1-traveling Hurricane Katrina are identical to the water surface levels induced by the original Hurricane Katrina at the London Avenue Canal site until the 15th hour of the numerical simulations (see the solid red line on Figure 4.32). Due to the absence of the breaches and/or overtopping of floodwalls and levees along Lake Pontchartrain, the residual water surface elevations for the Route 1-traveling Hurricane Katrina are much higher than the ones for the original Hurricane Katrina after the 15th hour of the numerical simulations. Hence, this is an evidential proof that the tremendous amount of water escaping from Lake Pontchartrain through the breaches and/or overtopping of floodwalls and levees can bring a devastating damage to the communities surrounding Lake Pontchartrain.

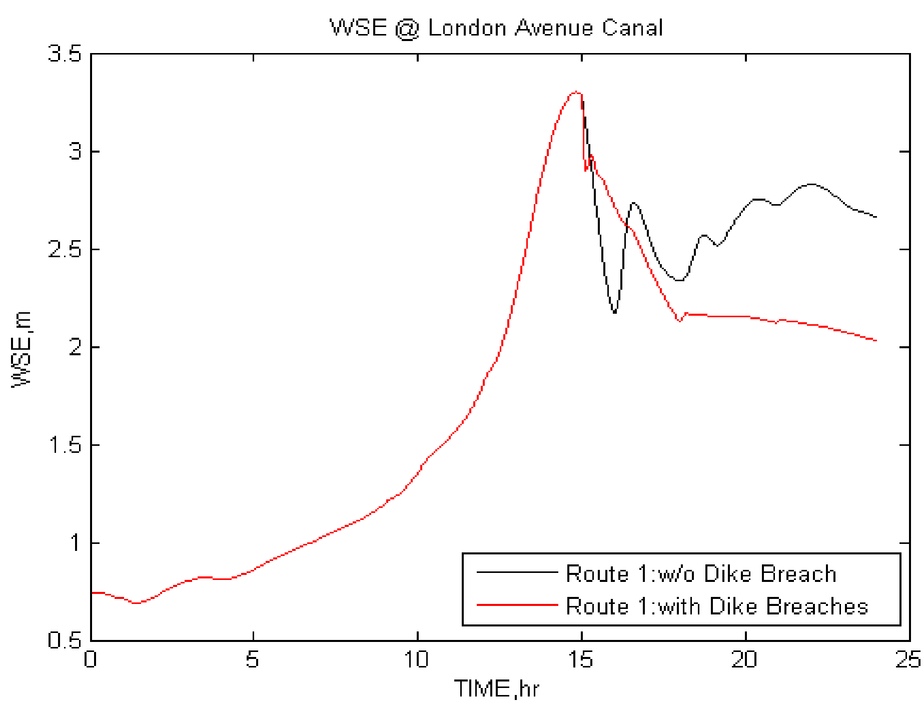

Figure 4.32 Computed Hydrograph, London Avenue Canal

The computed hydrograph (solid black line) obtained from the present model for the IHNC-Lakefront Airport is presented on Figure 4.33. From Figure 4.33, it is seen that the peak water surface elevation (WSE, so called water level in the IPET report) computed by the present model is approximately 3.30 m at the IHNC-Lakefront Airport site. In detail, the water surface elevations induced by the Route 1-traveling Hurricane Katrina are identical to the water surface levels induced by the original Hurricane Katrina at the IHNC-Lakefront Airport site until the 15th hour of the numerical simulations (see the solid red line on Figure 4.33). Due to the absence of the breaches and/or overtopping of floodwalls and levees along Lake Pontchartrain, the residual water surface elevations for the Route 1-traveling Hurricane Katrina are much higher than the ones for the original Hurricane Katrina after the 15th hour of the numerical simulations. Hence, this is an evidential proof that the tremendous amount of water escaping from Lake Pontchartrain through the breaches and/or overtopping of floodwalls and levees can bring a devastating damage to the communities surrounding Lake Pontchartrain.

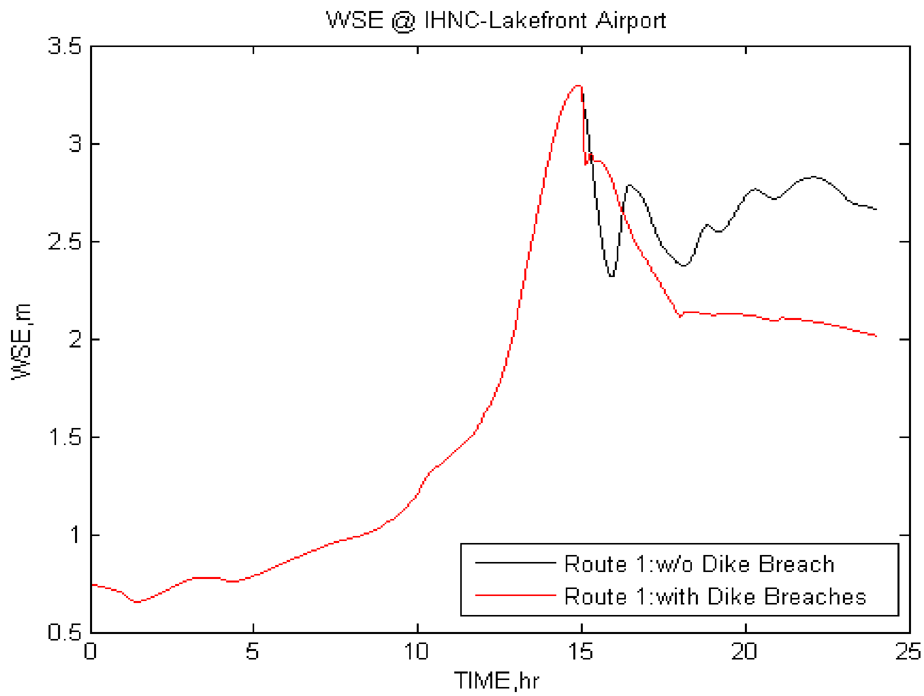

Figure 4.33 Computed Hydrograph, IHNC-Lakefront Airport

The computed hydrograph (solid black line) obtained from the present model for the Midlake is presented on Figure 4.34. From Figure 4.34, it is seen that the peak water surface elevation induced by the Route 1-traveling Hurricane Katrina is higher than the peak water surface level induced by the original Hurricane Katrina at the Midlake site (see the solid red line on Figure 4.34). Furthermore, the general trend of the rise and fall of water level induced by the wind generated by the Route 1-traveling Hurricane Katrina is slightly different from the general trend of the rise and fall of water level induced by the wind generated by the original Hurricane Katrina. Due to the absence of the breaches and/or overtopping of floodwalls and levees along Lake Pontchartrain, the residual water surface elevations for the Route 1-traveling Hurricane Katrina are much higher than the ones for the original Hurricane Katrina after the 15th hour of the numerical simulations. Hence, this is an evidential proof that the tremendous amount of water escaping from Lake Pontchartrain through the breaches and/or overtopping of floodwalls and levees can bring a devastating damage to the communities surrounding Lake Pontchartrain.

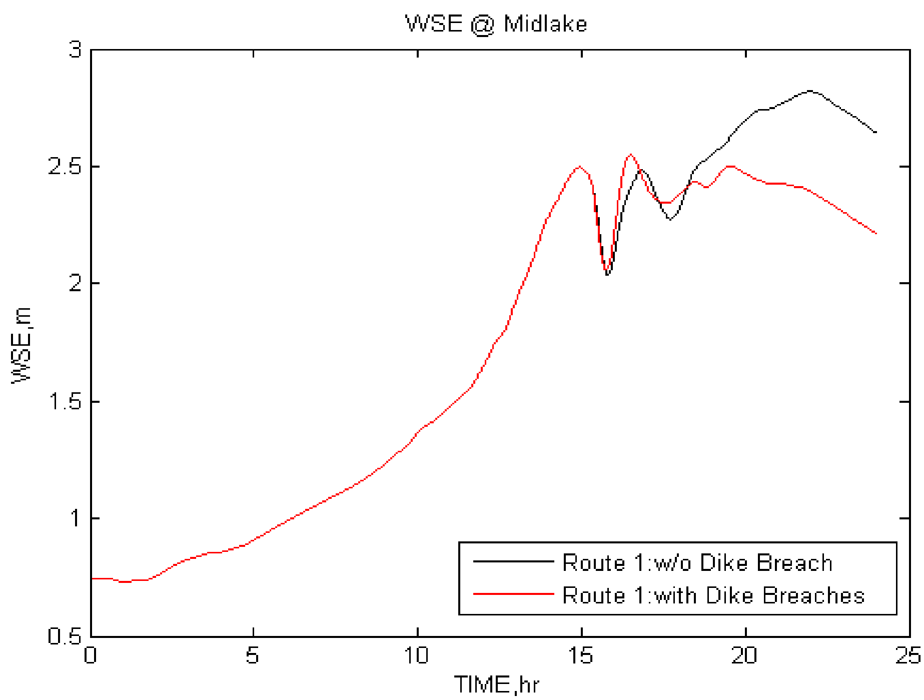

Figure 4.34 Computed Hydrograph, Midlake

The computed hydrograph (solid black line) obtained from the present model for Bayou La Branche (named Bayou Labranch in the IPET report) is presented on Figure 4.35. It can be seen from Figures 4.7 and 4.13 that Bayou La Branche is in the swamp along the southwest shore of Lake Pontchartrain and the swamps along the entire southwest shore of Lake Pontchatrain have been assigned into the computational domain for the current

numerical simulations performed by the present model. From Figure 4.35, it is seen that the peak water surface elevation induced by the Route 1-traveling Hurricane Katrina is equal to the peak water surface level induced by the original Hurricane Katrina at Bayou La Branche site (see the solid red line on Figure 4.35). Furthermore, the general trend of the rise and fall of water level induced by the wind generated by the Route 1-traveling Hurricane Katrina is slightly different from the general trend of the rise and fall of water level induced by the wind generated by the original Hurricane Katrina. Due to the absence of the breaches and/or overtopping of floodwalls and levees along Lake Pontchartrain, the residual water surface elevations for the Route 1-traveling Hurricane Katrina are much higher than the ones for the original Hurricane Katrina after the 15th hour of the numerical simulations. Hence, this is an evidential proof that the tremendous amount of water escaping from Lake Pontchartrain through the breaches and/or overtopping of floodwalls and levees can bring a devastating damage to the communities surrounding Lake Pontchartrain.

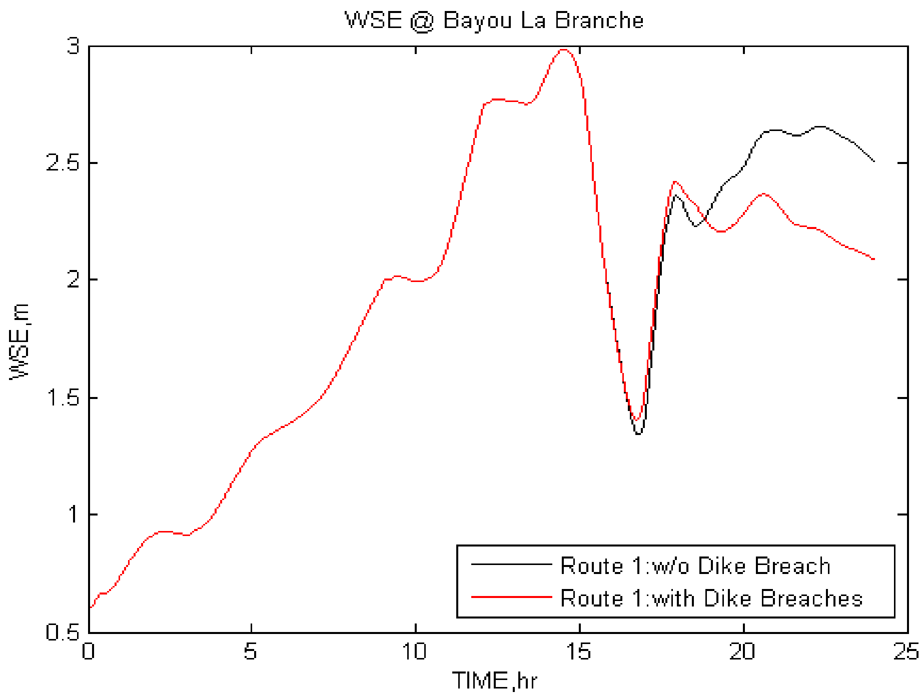

Figure 4.35 Computed Hydrograph, Bayou La Branche

The computed hydrograph (solid black line) obtained from the present model for Pass Manchac-Turtle Cove is presented on Figure 4.36. From Figures 4.7 and 4.13, it can be seen that Pass Manchac is a the narrow strip of water connecting Lake Pontchartrain and Lake Maurepas and the entire Pass Manchac is included in the computational domain used in the current numerical simulations performed by the present model. From Figure 4.36, it is seen that the peak water surface elevation induced by the Route 1-traveling Hurricane Katrina is higher than the peak water surface level induced by the original Hurricane Katrina at Pass Manchac-Turtle Cove site (see the solid red line on Figure 4.36). Furthermore, the general trend of the rise and fall of water level induced by the wind generated by the Route 1-traveling Hurricane Katrina is slightly different from the general trend of the rise and fall of water level induced by the wind generated by the original Hurricane Katrina. Due to the absence of the breaches and/or overtopping of floodwalls and levees along Lake Pontchartrain, the residual water surface elevations for the Route 1-traveling Hurricane Katrina are much higher than the ones for the original Hurricane Katrina after the 15th hour of the numerical simulations. Hence, this is an evidential proof that the tremendous amount of water escaping from Lake Pontchartrain through the breaches and/or overtopping of floodwalls and levees can bring a devastating damage to the communities surrounding Lake Pontchartrain.

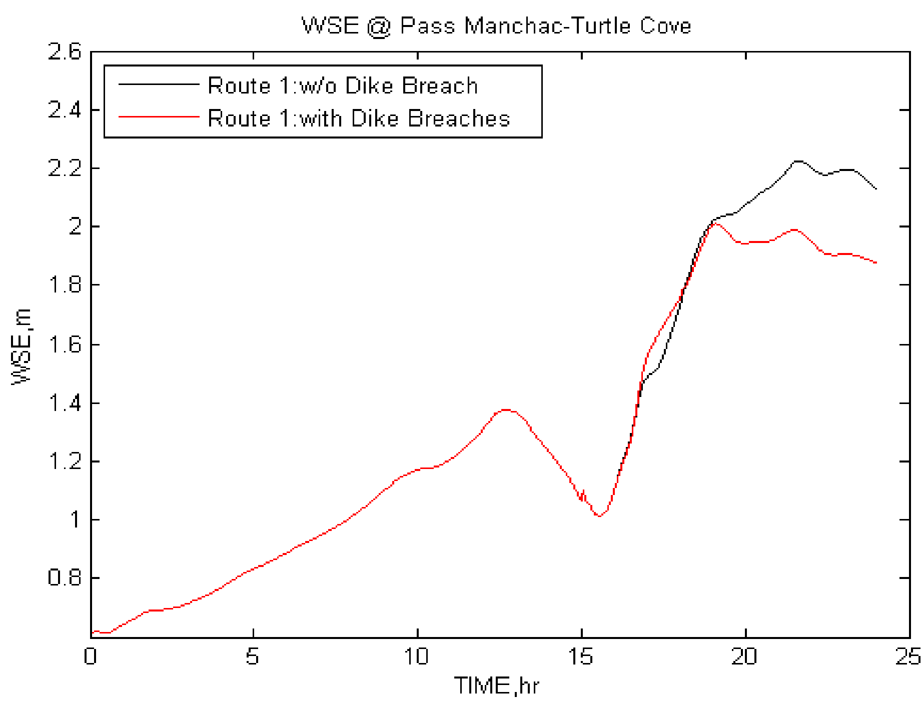

Figure 4.36 Computed Hydrograph, Pass Manchac-Turtle Cove

The computed hydrograph (solid black line) obtained from the present model for Little Irish Bayou is presented on Figure 4.37. From Figure 4.37, it is seen that the peak water surface elevation induced by the Route 1-traveling Hurricane Katrina is slightly higher than the peak water surface level induced by the original Hurricane Katrina at Little Irish Bayou site (see the solid red line on Figure 4.37). Furthermore, the general trend of the rise and fall of water level induced by the wind generated by the Route 1-traveling Hurricane Katrina is slightly different from the general trend of the rise and fall of water level induced by the wind generated by the original Hurricane Katrina. Due to the absence of the breaches and/or overtopping of floodwalls and levees along Lake Pontchartrain, the residual water surface elevations for the Route 1-traveling Hurricane Katrina are much higher than the ones for the original Hurricane Katrina after the 15th hour of the numerical simulations. Hence, this is an evidential proof that the tremendous amount of water escaping from Lake Pontchartrain through the breaches and/or overtopping of floodwalls and levees can bring a devastating damage to the communities surrounding Lake Pontchartrain.

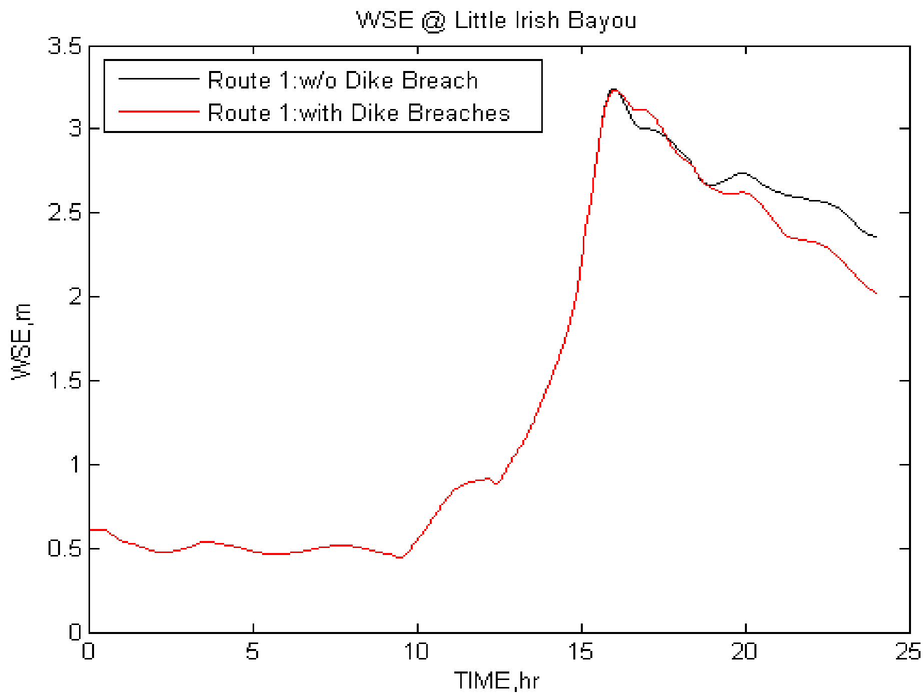

Figure 4.37 Computed Hydrograph, Little Irish Bayou

The computed hydrographs of the water surface elevation (WSE) showing on S-N and W-E cross-sections of Lake Pontchartrain induced by the wind generated through the Route 1-traveling Hurricane Katrina are presented on Figures 4.38 and 4.39, respectively. It is seen from Figures 4.38 and 4.39 that the wind-induced oscillations in Lake Pontchartrain are the evident phenomena as Hurricane Katrina progressed over the Southeast Louisiana region (Route 1 shown in Figure 4.28). In the following paragraphs, the hourly contour maps of the water surface elevation (WSE) for the entire Lake Pontchartrain, as Hurricane Katrina progressed over the Southeast Louisiana region (Route 1 shown in Figure 4.28, which is the exact route of Hurricane Katrina), are used to investigate the oscillations of semi-enclosed water body induced by hurricanes under specific routes.

The hourly contour maps of the computed water surface elevation (WSE) for the entire Lake Pontchartrain induced by the wind generated through the original Hurricane Katrina are presented from Figures 4.40 to Figures 4.64. The time-frame of these contour maps is from 12:00 am UTC August 29, 2005 to 12:00 am UTC August 30, 2005. It is assigned that $t = 0$ is at 11:59:15 pm UTC August 28, 2005 and consequently the reference WSE at $t = 0$ is zero. Therefore, the oscillation phenomenon is not evident throughout entire Lake Pontchartrain at the starting moment of the numerical simulation (12:00 am August 29, 2005), as it is seen from Figure 4.40. As it is seen from Figures 4.2 and 4.28, the original Hurricane Katrina did not make its landfall until 6:10 am CDT (11:10 am UTC) August 29 at Southeast Louisiana and the Route 1 is the exact route of the original Hurricane Katrina; besides, the oscillation induced by tides from Gulf of Mexico into Lake Pontchartrain is not influential in this study, this is a reasonable assumption that the oscillations in Lake Pontchartrain induced by wind generated by the Route 1-traveling Hurricane Katrina can be focused on the 24-hours period between 12:00 am UTC August 29, 2005 and 12:00 am UTC August 30, 2005.

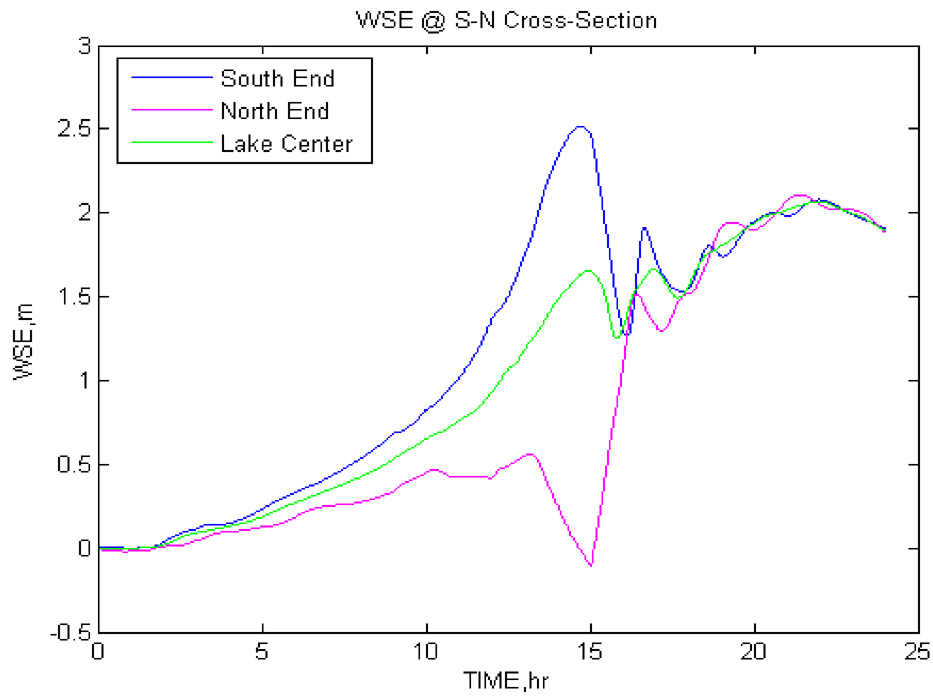

Figure 4.38 Hydrographs of the S-N cross-section

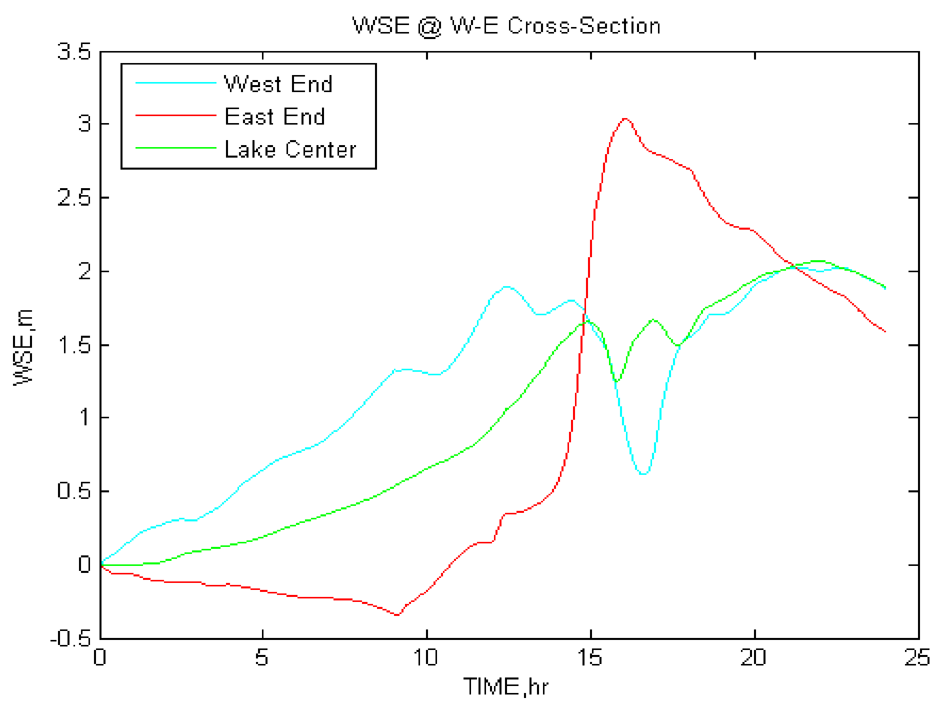

Figure 4.39 Hydrographs of the W-E cross-section

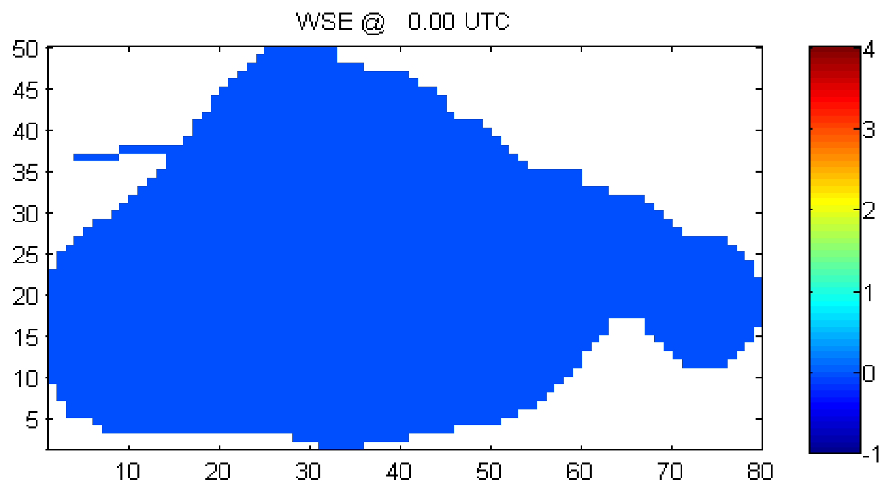

Figure 4.40 Contours of WSE at 12:00 am (UTC) August 29, 2005

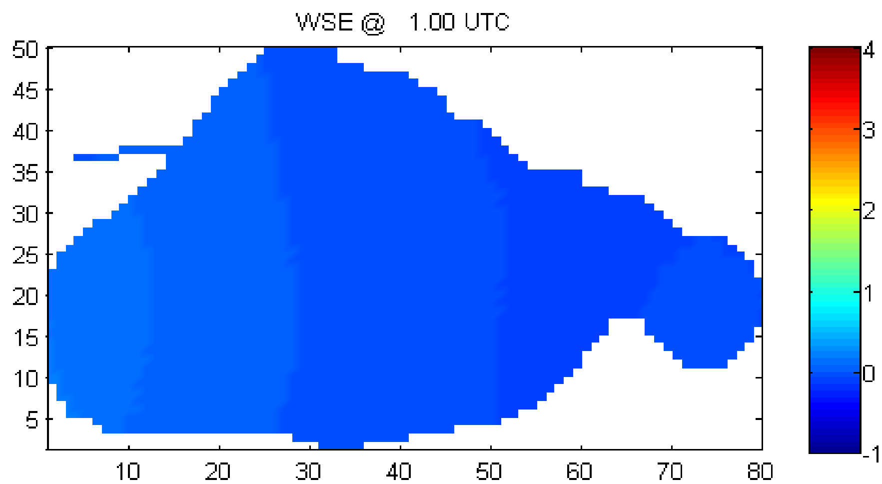

Figure 4.41 Contours of WSE at 01:00 am (UTC) August 29, 2005

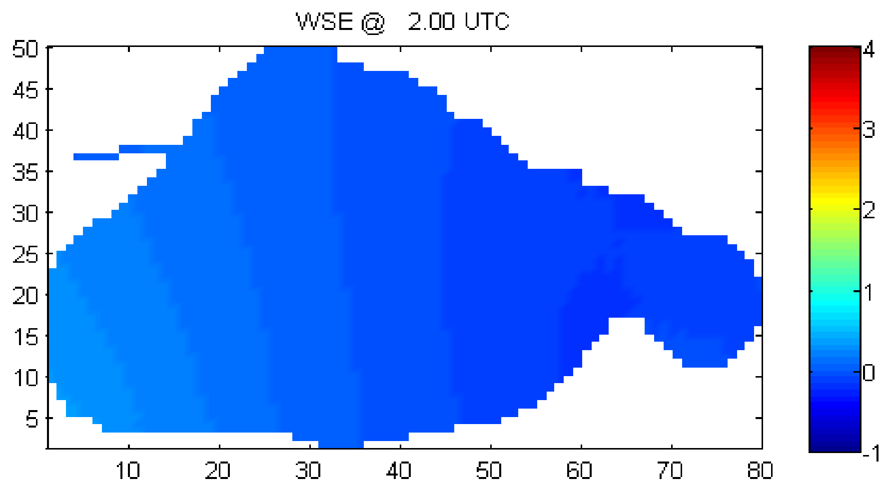

Figure 4.42 Contours of WSE at 02:00 am (UTC) August 29, 2005

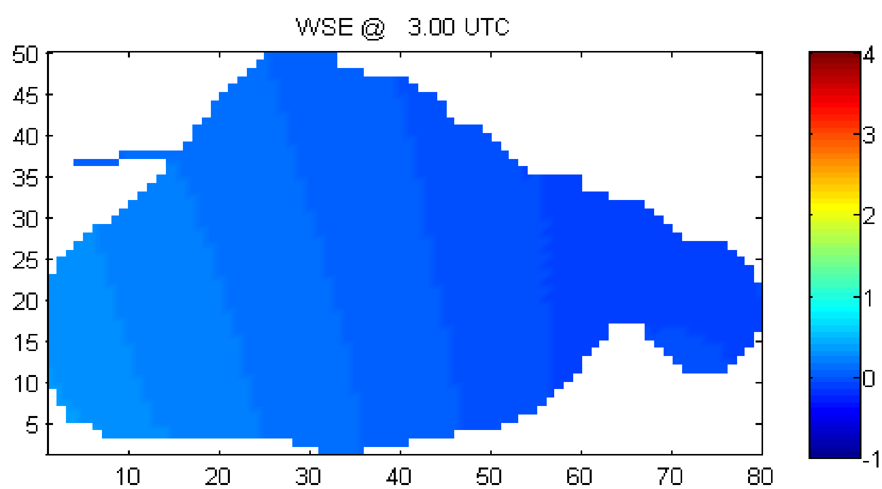

Figure 4.43 Contours of WSE at 03:00 am (UTC) August 29, 2005

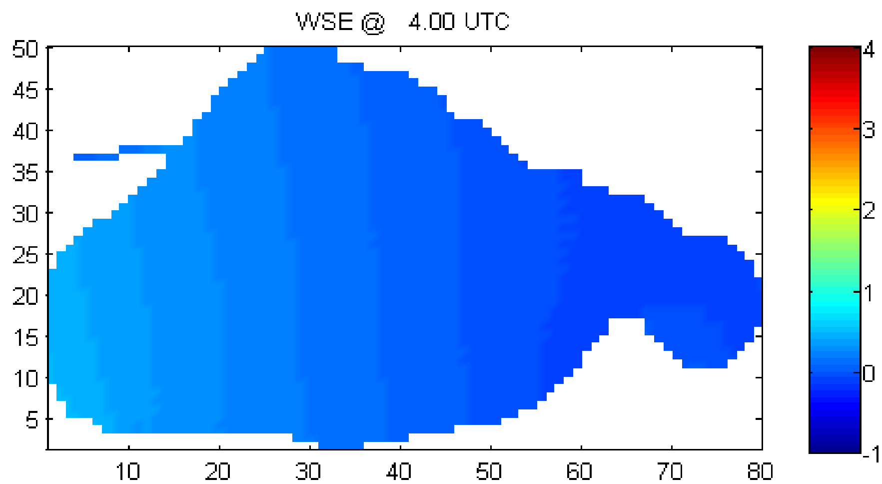

Figure 4.44 Contours of WSE at 04:00 am (UTC) August 29, 2005

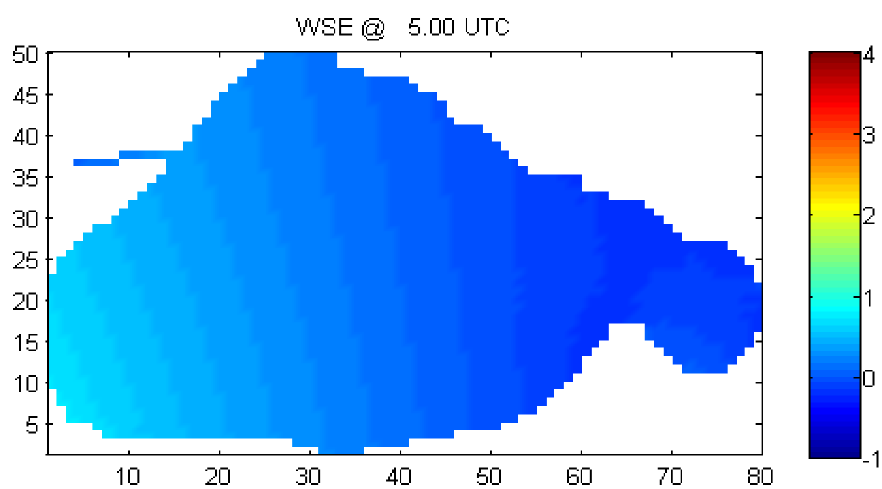

Figure 4.45 Contours of WSE at 05:00 am (UTC) August 29, 2005

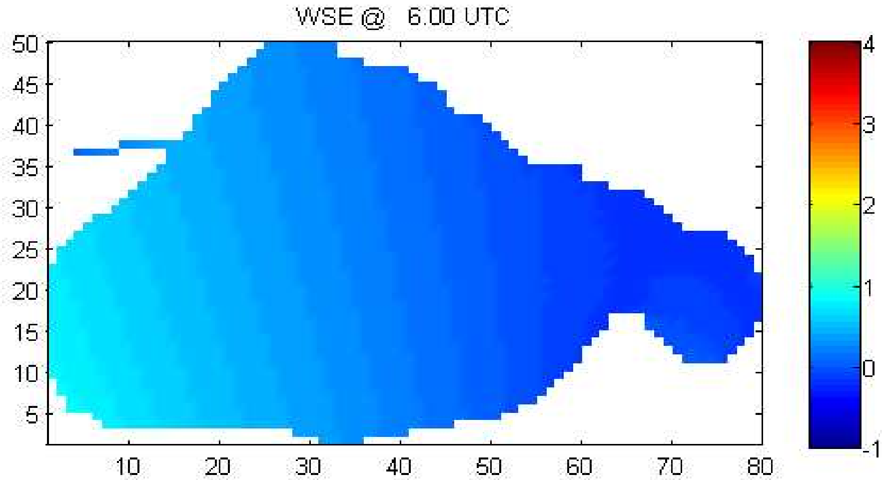

Figure 4.46 Contours of WSE at 06:00 am (UTC) August 29, 2005

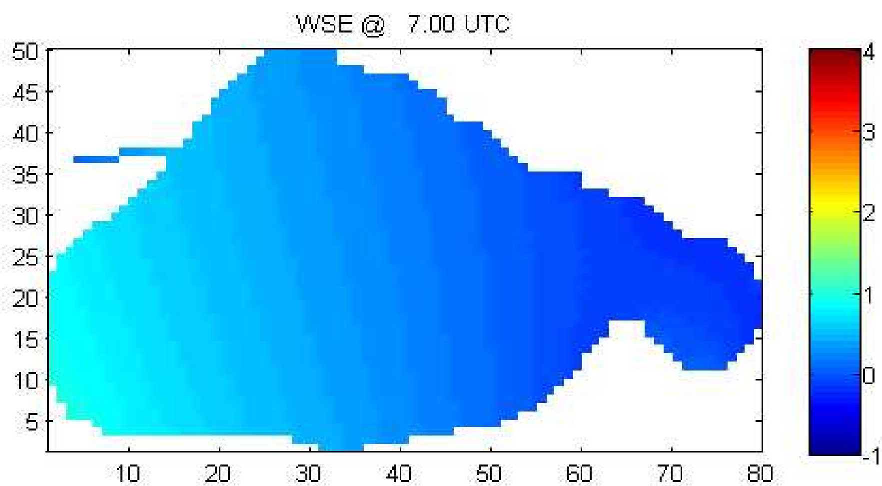

Figure 4.47 Contours of WSE at 07:00 am (UTC) August 29, 2005

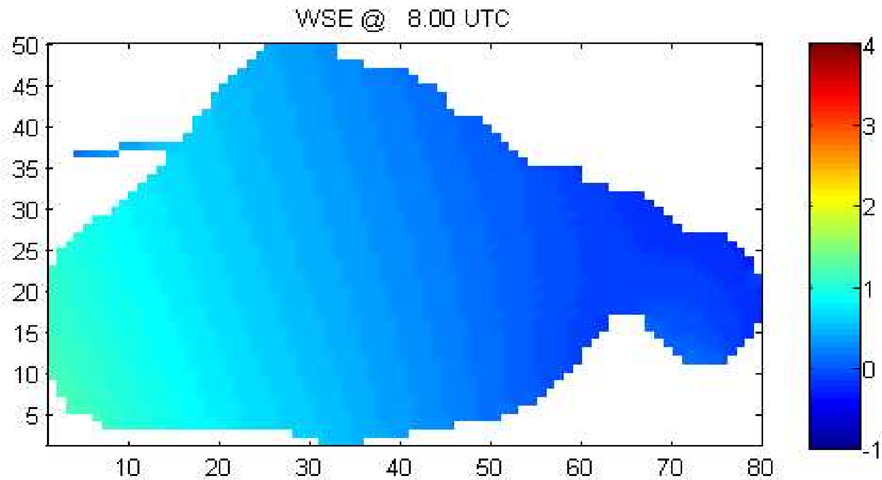

Figure 4.48 Contours of WSE at 08:00 am (UTC) August 29, 2005

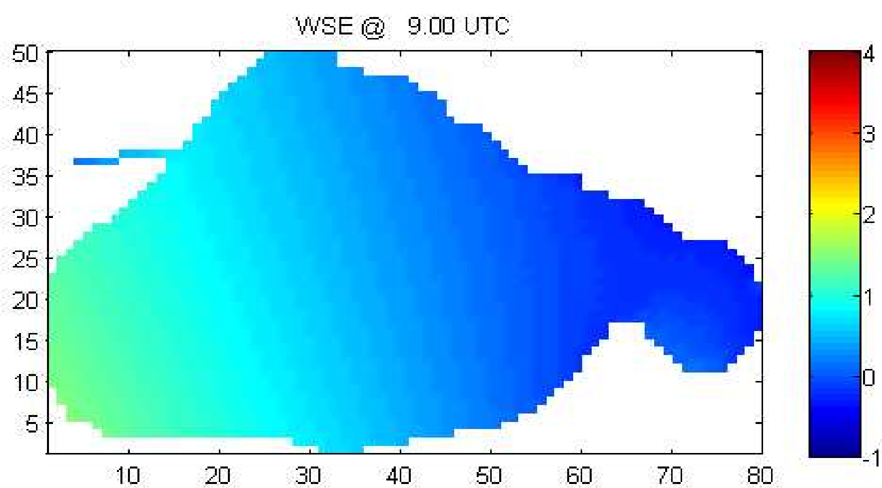

Figure 4.49 Contours of WSE at 09:00 am (UTC) August 29, 2005

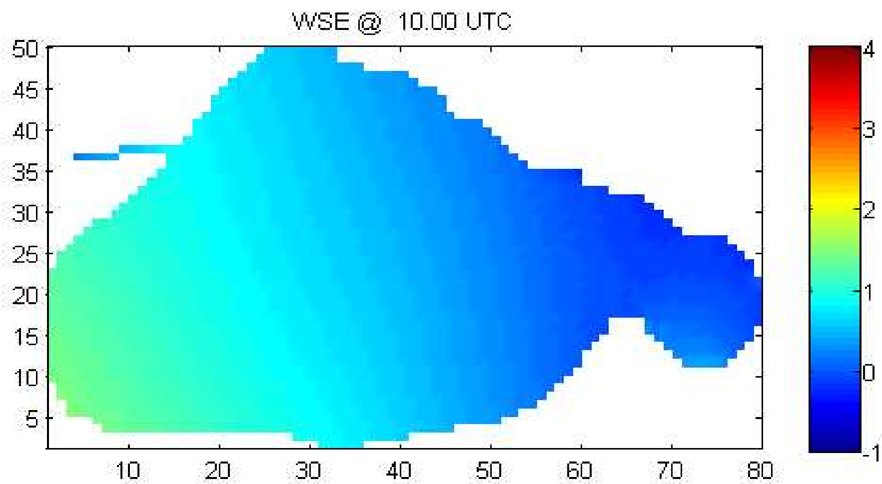

Figure 4.50 Contours of WSE at 10:00 am (UTC) August 29, 2005

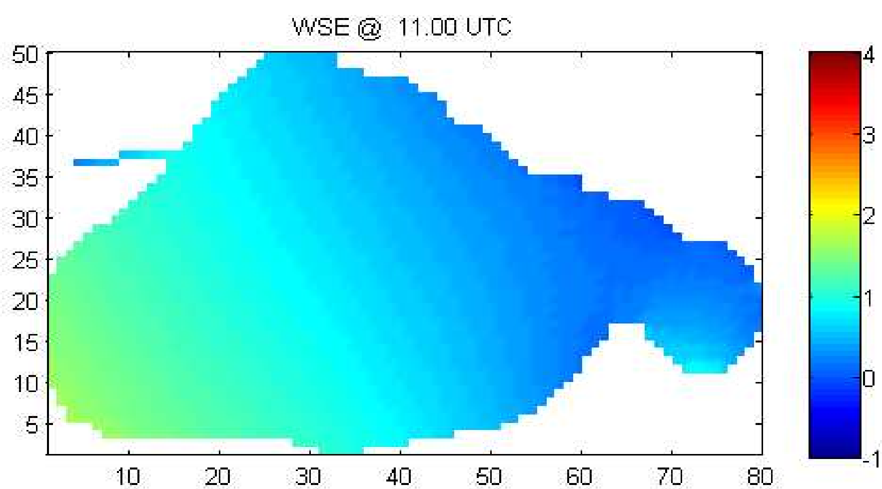

Figure 4.51 Contours of WSE at 11:00 am (UTC) August 29, 2005

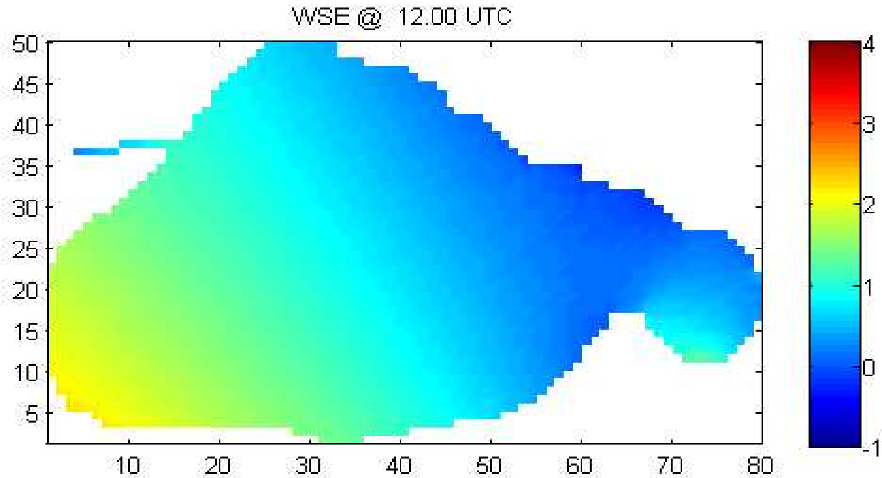

Figure 4.52 Contours of WSE at 12:00 pm (UTC) August 29, 2005

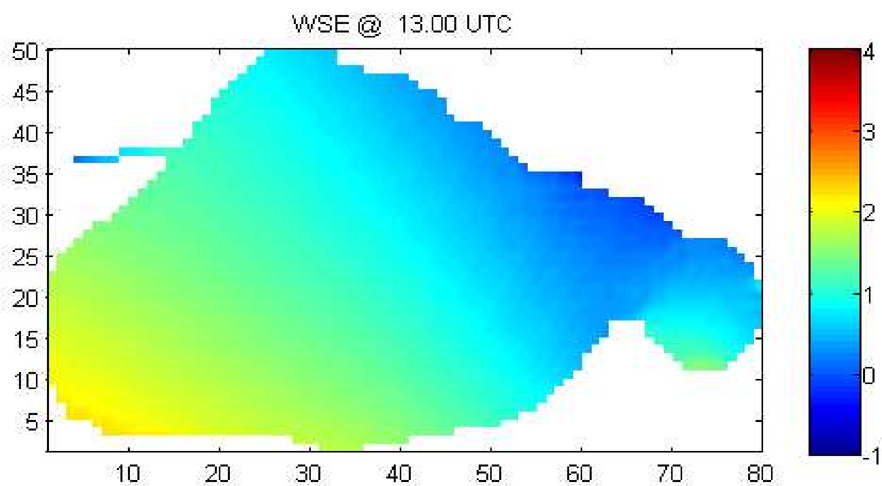

Figure 4.53 Contours of WSE at 01:00 pm (UTC) August 29, 2005

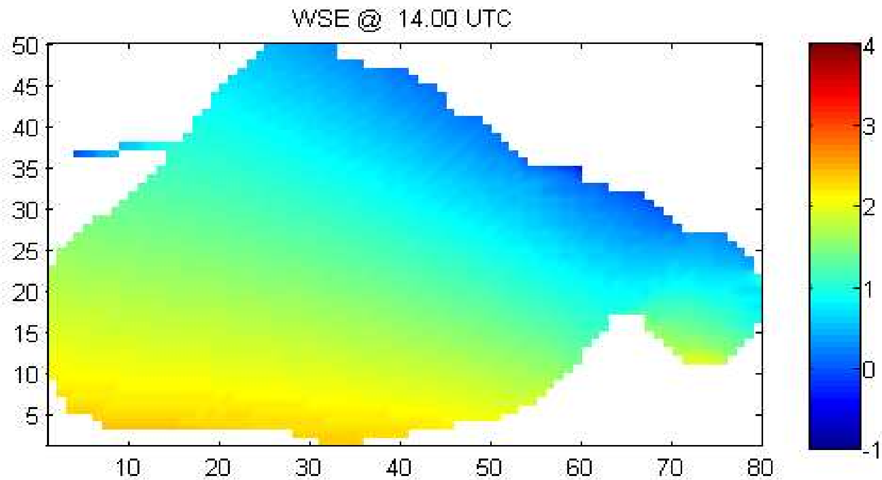

Figure 4.54 Contours of WSE at 02:00 pm (UTC) August 29, 2005

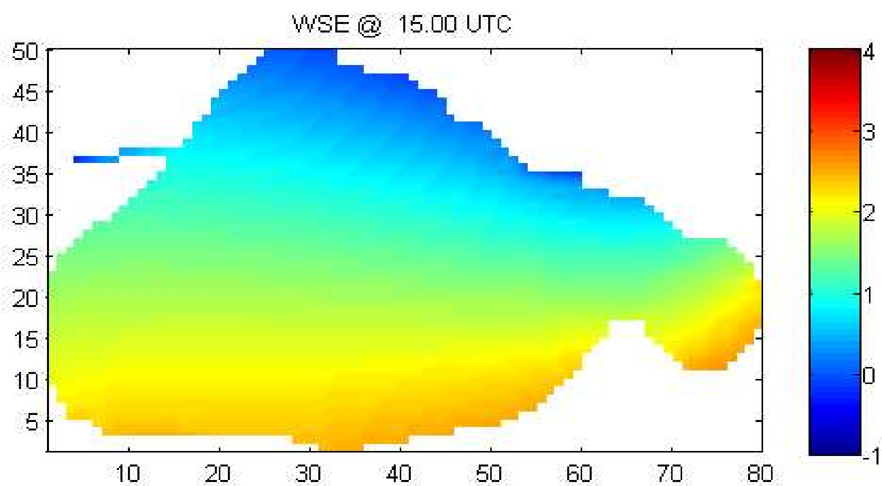

Figure 4.55 Contours of WSE at 03:00 pm (UTC) August 29, 2005

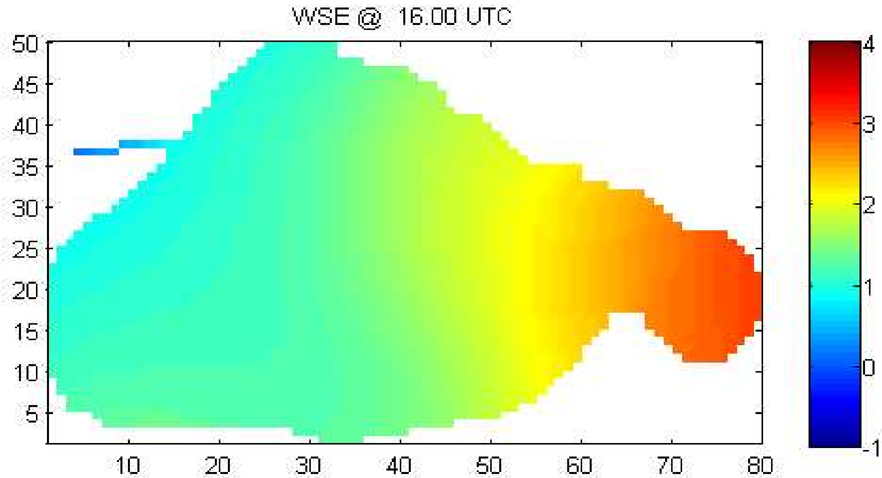

Figure 4.56 Contours of WSE at 04:00 pm (UTC) August 29, 2005

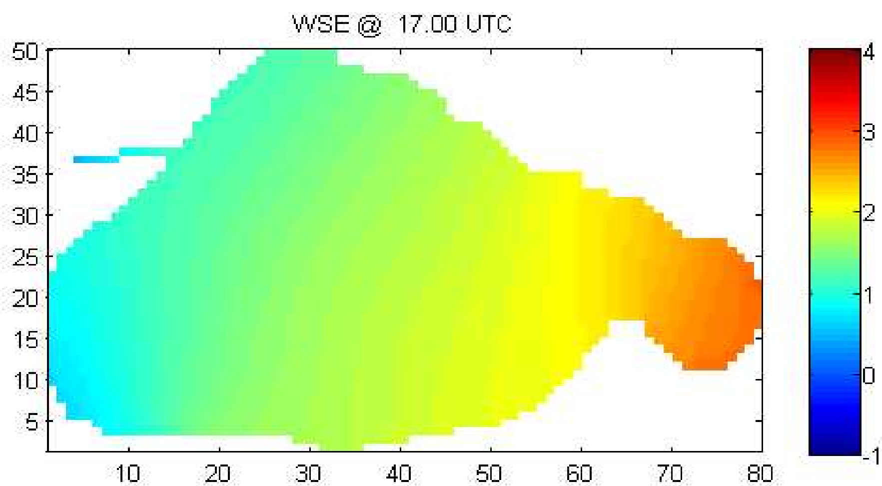

Figure 4.57 Contours of WSE at 05:00 pm (UTC) August 29, 2005

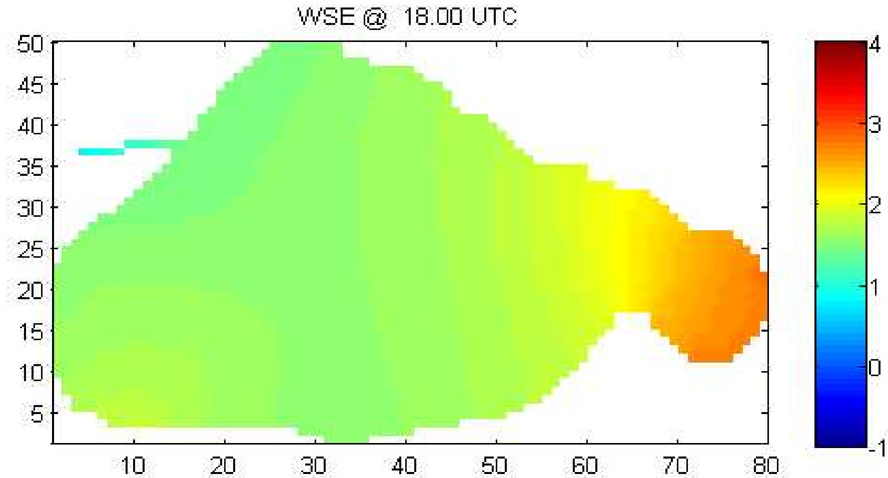

Figure 4.58 Contours of WSE at 06:00 pm (UTC) August 29, 2005

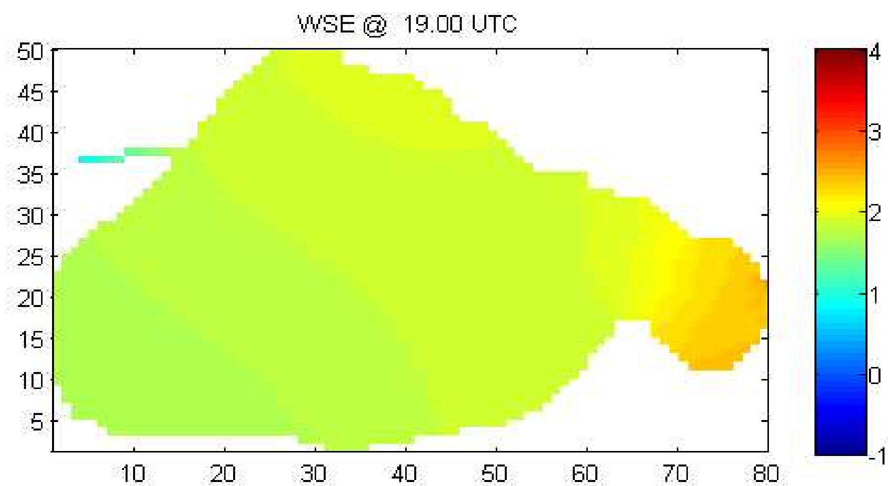

Figure 4.59 Contours of WSE at 07:00 pm (UTC) August 29, 2005

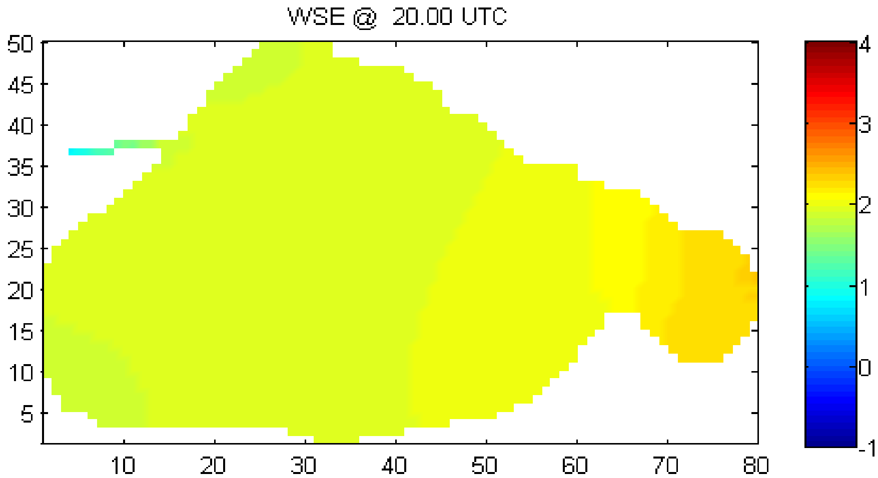

Figure 4.60 Contours of WSE at 08:00 pm (UTC) August 29, 2005

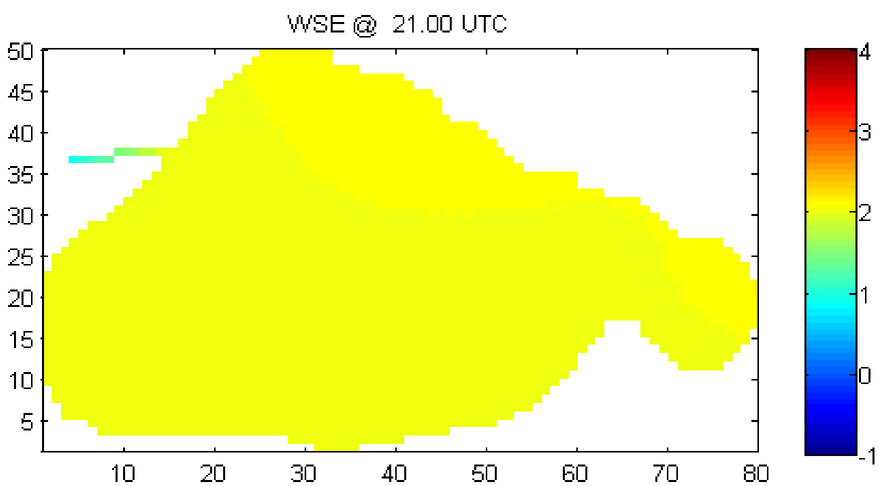

Figure 4.61 Contours of WSE at 09:00 pm (UTC) August 29, 2005

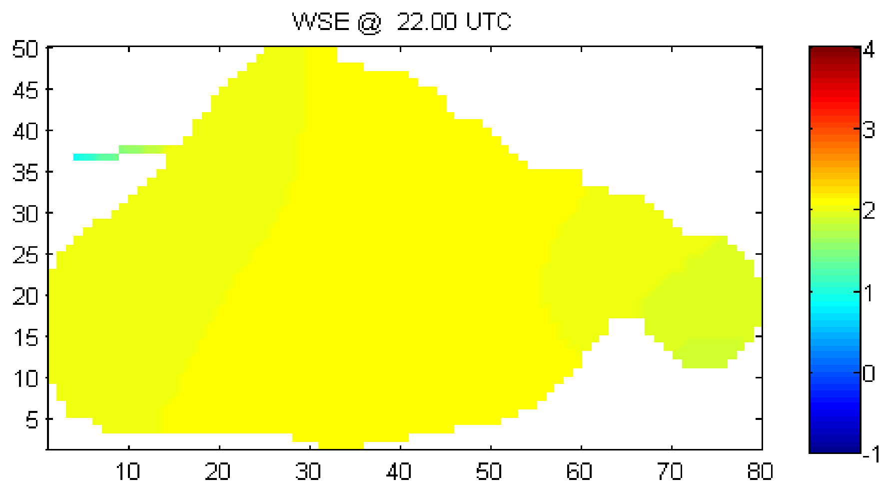

Figure 4.62 Contours of WSE at 10:00 pm (UTC) August 29, 2005

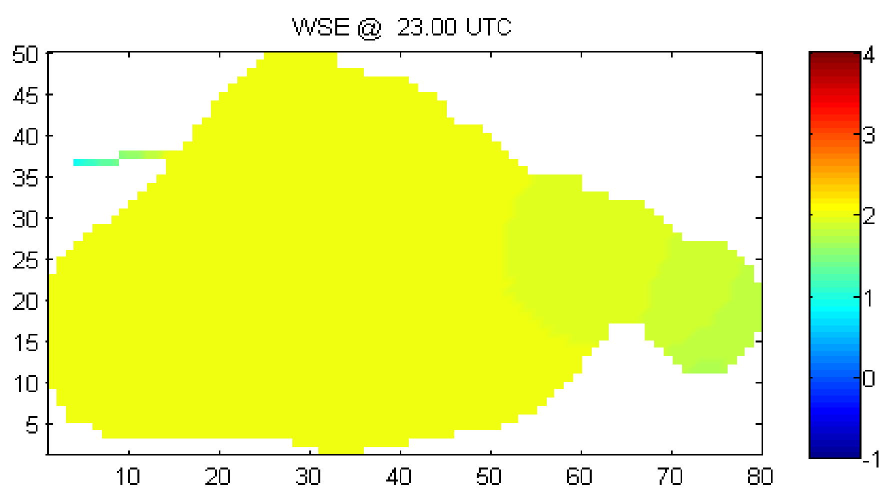

Figure 4.63 Contours of WSE at 11:00 pm (UTC) August 29, 2005

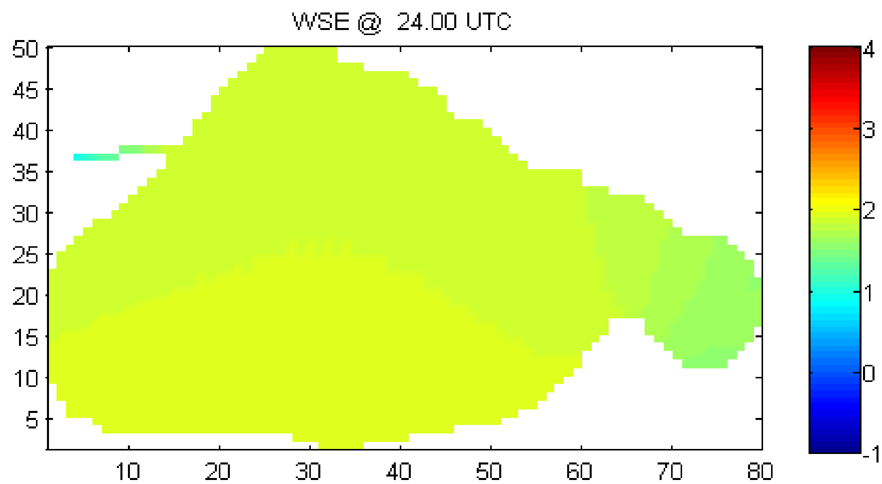

Figure 4.64 Contours of WSE at 12:00 am (UTC) August 30, 2005

It can be seen from Figures 4.41 to 4.46 that the oscillation in Lake Pontchartrain is built up as Hurricane Katrina approaches to Southeast Louisiana and it becomes more obvious as time goes by. It is very evident that the direction of node line ($\eta = 0$) in the lake is in the North-South orientation. It is seen that the water in the east part of the lake is driven by the wind to the west part of the lake during the first 6-hour period, as we examine the temporal variations of the contours of WSE from 12:00 to 06:00 am UTC August 29, 2005. The strength of Hurricane Katrina, according to the IPET report, is gradually reducing from Category 4 to 3 in Saffir-Simpson Scale within this 6-hours period.

As the hurricane approaches Southeast Louisiana and makes its first landfall at approximately 11:10 am UTC (6:10 am Local Time) August 29, the magnitude of oscillation in the lake gradually increases between 07:00 am UTC and 12:00 pm UTC August 29, 2005. During this 6-hours period, the direction of node line ($\eta = 0$) in the lake slowly changes from the North-South orientation to the Northwest-Southeast orientation since the direction of the dominant wind alters as Hurricane Katrina approaches to Lake Pontchartrain while its strength remains Category 3. We can see these phenomena after examining the temporal variations of the contours of WSE from Figures 4.47 to 4.52.

From 12:00 pm UTC to 03:00 pm UTC August 29, Hurricane Katrina passes nearby the east shore of Lake Pontchartrain. Thus, this close-encounter between the hurricane and the lake causes significant oscillations in Lake Pontchartrain as we compare the oscillations happened in the lake during the previous 12 hours. It is seen from Figures 4.53 to 4.55 that the direction of node line ($\eta = 0$) in the lake changes from the Northwest-Southeast orientation to the West-East orientation as the direction of the dominant wind rapidly alters during this 3-hours period. Meanwhile, the magnitude of oscillation (the height of WSE) becomes higher than the previous 6 hours, and the oscillation along the south shore of Lake Pontchartrain reaches the highest magnitude between 02:30 and 03:00 pm UTC (or 09:30 and 10:00 am Local Time), as we have already seen from Figures 4.30 to 4.33. Within this 3-hours period, Hurricane Katrina makes its second landfall at approximately 02:45 pm UTC (09:45 am Local Time) near

Louisiana/Mississippi border (as it is seen from Route 1 shown in Figure 4.28) and its strength still remains Category 3.

During the next 3-hours period (from 03:00 to 06:00 pm UTC August 29), the Hurricane Katrina continuously moves inland with a nearly north direction and its strength reduces from Category 3 to 2. Meanwhile, the direction of node line ($\eta = 0$) rapidly turns from the West-East orientation to the South-North orientation as the direction of the dominant wind alters 90° in a counterclockwise pattern even though the wind generated by the hurricane gets weaker during this 3-hours time-period. Because the surge propagates into Lake Pontchartrain from the Gulf of Mexico via Lake Borgne (see Figure 4.3), an enormous amount of water flows into Lake Pontchartrain and the magnitude of oscillation (the height of WSE) in Lake Pontchartrain significantly increases even though the hurricane leaves the northeast regions of the lake. Furthermore, the node line ($\eta = 0$) disappears and the WSE in the entire lake is greater than the reference WSE ($\eta = 0$) from 04:00 pm, as it is seen from Figure 4.56. We can find these evidences from a thorough study of the temporal variations of the contours of WSE from Figures 4.56 to 4.58.

In the final 6-hours period (from 07:00 pm UTC August 29 to 12:00 am UTC August 30, 2005), the strength of Hurricane Katrina continuously reduces from Category 2 to 1 and finally Hurricane Katrina becomes a tropical storm as it moves inwardly into the northeastern region of the United States of America. Although the direction of dominant wind keeps turning counterclockwise during this 6-hours period, the wind generated by the hurricane is drastically weaker than it was in the previous 18-hours period. Since the hurricane moves far away from the lake, the magnitude of oscillation in Lake Pontchartrain gradually reduces and is smaller than it was in the previous 6-hour period. Besides, the major sloshing motion is moving toward the east within this 6-hours period. The WSE in the lake does not significantly recede since there is not enough wind stress to drive out the water from Lake Pontchartrain to Lake Borgne and other surrounding water bodies; hence, the WSE in the entire lake is greater than the reference WSE ($\eta = 0$) in this 6-hours period. Meanwhile, there is a significant drawdown in the east portion of Lake Pontchartrain at the finale of the numerical simulation (12:00 am August 30, 2005) as it is seen from Figure 4.64. We can obtain these discoveries by examining the temporal variations of WSE from Figures 4.59 to 4.64. Furthermore, the significant findings drawn from these hourly contour maps (from Figures 4.40 to 4.64) are summarized in the following paragraphs.

The Route 1-traveling Hurricane Katrina moves in a nearly north direction and passes through the regions close to the east shore of Lake Pontchartrain (Route 1 shown in Figure 4.28) between 12:00 am and 06:00 pm UTC August 29, 2005 corresponding to the first 18-hours of the numerical simulations made by the present model. The closest encounter between Hurricane Katrina and Lake Pontchartrain takes place between 12:00 and 06:00 pm UTC (or 7:00 am and 1:00 pm Local Time) August 29, 2005 (see Figure

4.2). During this 6-hours period, there are three significant factors of Hurricane Katrina needed to be reviewed:

1. The hurricane remains Category 3 intensity of Saffir-Simpson Scale until 03:00 pm UTC (10:00 am Local Time), after which the strength of the hurricane gradually reduces to Category 2.
2. The hurricane is moving in a nearly north direction with an approximate speed of 27 to 29 km/hr.
3. The distance between the eye of the hurricane and the east shore of the lake is approximately 12 km.

Because of these three unique characteristics of the interaction between the hurricane and the lake, the sloshing motion of the lake water surface changes in a counterclockwise pattern in the lake as the hurricane itself rotates in the counterclockwise character. In detail, the dominant sloshing motion at Lake Pontchartrain turns from the southwest to the east within this 6-hours period. During this 6-hours, the highest amplitude of oscillation (maximum WSE) along the south shore of the lake happens around 03:00 pm UTC (10:00 am Local Time) with a magnitude of 3.27 m to 3.30 m predicted by the present model while the highest measured water level associated with this 6-hours period is within the range of 10.8 ft to 12.0 ft (or 3.29 m to 3.66 m) along the south shore of Lake Pontchartrain.

Furthermore, the moving direction of the storm surge changes from the west direction to the east direction within the first 16-hours period (12:00 am to 04:00 pm UTC August 29, 2005) of the numerical simulations (see Figures 4.40 to 56); in other words, the sloshing motion changes 180° in 16 hours. Therefore, the oscillation (rise and fall of water level) in a semi-enclosed lake induced by a hurricane will be moving around the lake in a counterclockwise-turning pattern. While a hurricane circulates counterclockwise and the direction of the accompanying wind generated by the hurricane turns in a counterclockwise pattern, the magnitude of oscillation thoroughly depends on the strength (wind speed) and the duration (length in time) of the wind to a specific direction. In other words, the magnitude of the oscillation (height of rise and fall) associated with the moving direction will be different at each specific location around the lake.

4.5.2 Hurricane Katrina Traveling Along Route 2

The present model is used to study the oscillation in Lake Pontchartrain induced by wind generated by the Route 2-traveling Hurricane Katrina (see Figure 4.28). The dimensions of the uniform rectangular control-volumes (CV's) in a Cartesian grid are $(\Delta x, \Delta y) = (750\,m, 750\,m)$. The time-step Δt is chosen to be 45 seconds. The bathymetry of Lake Pontchartrain adopted from the Interagency Performance Evaluation Task Force (IPET) report is used in the numerical simulations (see Figure 4.14). The time-period in the numerical simulations for the oscillation in Lake Pontchartrain induced by wind generated by the Route 2-traveling Hurricane Katrina is from 12:00 am UTC (Coordinated Universal Time) August 29, 2005 to 12:00 am UTC August 30, 2005, or 07:00 pm CDT (Central Daylight Time) August 28, 2005 to 07:00 pm CDT August 29, 2005. During this 24-hours time-period, Hurricane Katrina will make its landfall at Southeast Louisiana and will pass through the east part of New Orleans, Louisiana and above the central and east parts of Lake Pontchartrain (see Figures 4.2 and 4.28). Hence, the study of the oscillation in Lake Pontchartrain induced by wind generated by the Route 2-traveling Hurricane Katrina can be concentrated in this 24-hours period. In order to study the oscillation phenomena in Lake Pontchartrain induced by the Route-2 traveling Hurricane Katrina, the breaches and/or overtopping of floodwalls and levees along Lake Pontchartrain will not be accommodated into the numerical simulations performed by the present model for this case; hence, the water can not flow out of the lake through the entrances of the canals connecting to the lake during the entire 24-hours period of the numerical simulations for the oscillations of Lake Pontchartrain induced by the Route-2 traveling Hurricane Katrina.

The wind field inducing the oscillations in Lake Pontchartrain is exclusively caused by the Route 2-traveling Hurricane Katrina. The numerical typhoon (or hurricane) model, based on Equation (3.9) through Equation (3.14) in Chapter 3 and developed along with the present model in this study, is used to generate the pressure and wind fields. The meteorological data to simulate Hurricane Katrina between 12:00 am UTC August 29, 2005 and 12:00 am UTC August 30, 2005 are adopted from the Interagency Performance

Evaluation Task Force (IPET) report and are listed in Table 4.1. The diameters of the eye of the simulated Hurricane Katrina by the numerical hurricane model are the distances corresponding to a time interval of a half-hour traveling of the simulated Hurricane Katrina. The speeds for the simulated Hurricane Katrina derived from the moving path of Hurricane Katrina between 12:00 am UTC August 29, 2005 and 12:00 am UTC August 30, 2005 are interpreted from the hourly Latitudes and Longitudes of Hurricane Katrina recorded in the Interagency Performance Evaluation Task Force (IPET) report.

The computed hydrograph (solid black line) obtained from the present model for the 17th Street Canal is presented on Figure 4.65. From Figure 4.65, it is seen that the peak water surface elevation (WSE, so called water level in the IPET report) computed by the present model is approximately 3.86 m at the 17th Street Canal site. Besides, it is seen that the peak water surface elevation induced by the Route 2-traveling Hurricane Katrina is much higher than the peak water surface level induced by the Route 1-traveling Hurricane Katrina at the 17th Street Canal site (3.86 m versus 3.30 m) after comparing the computed hydrograph made under the wind generated by the Route 2-traveling Hurricane Katrina with the one made under the wind generated by the Route 1-traveling Hurricane Katrina (see the solid red line on Figure 4.65). Therefore, it can be claimed that this significant difference in water surface elevation is caused by a hurricane passing over Lake Pontchartrain with another route although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

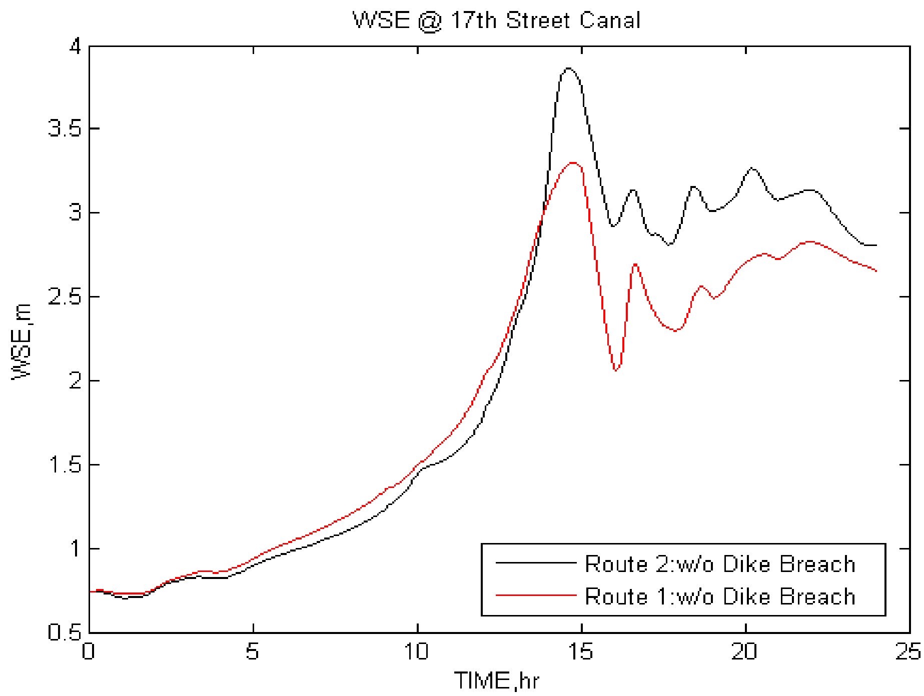

Figure 4.65 Computed Hydrograph, 17th Street Canal

The computed hydrograph (solid black line) obtained from the present model for the Orleans Avenue Canal is presented on Figure 4.66. From Figure 4.66, it is seen that the peak water surface elevation (WSE, so called water level in the IPET report) computed by the present model is approximately 3.53 m at the Orleans Avenue Canal site. Besides, it is seen that the peak water surface elevation induced by the Route 2-traveling Hurricane Katrina is much higher than the peak water surface level induced by the Route 1-traveling Hurricane Katrina at the Orleans Avenue Canal site (3.53 m versus 3.27 m) after comparing the computed hydrograph made under the wind generated by the Route 2-traveling Hurricane Katrina with the one made under the wind generated by the Route 1-traveling Hurricane Katrina (see the solid red line on Figure 4.66). Therefore, it can be claimed that hurricane passing over Lake Pontchartrain with another route can cause a significant difference in water surface elevation although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

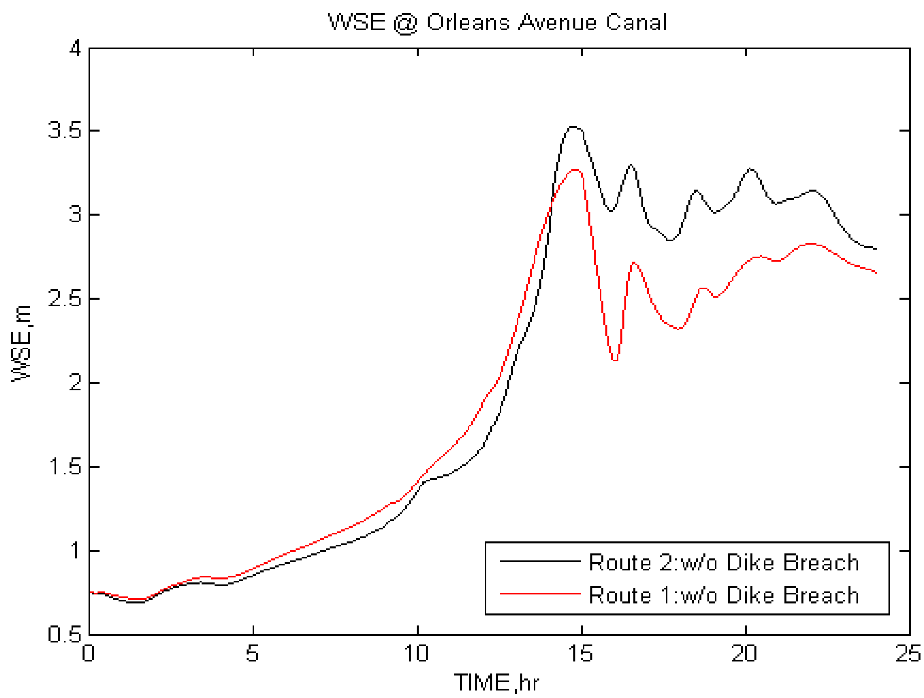

Figure 4.66 Computed Hydrograph, Orleans Avenue Canal

The computed hydrograph (solid black line) obtained from the present model for the London Avenue Canal is presented on Figure 4.67. From Figure 4.67, it is seen that the peak water surface elevation (WSE, so called water level in the IPET report) computed by the present model is approximately 3.53 m at the London Avenue Canal site. Besides, it is seen that the peak water surface elevation induced by the Route 2-traveling Hurricane Katrina is much higher than the peak water surface level induced by the Route

1-traveling Hurricane Katrina at the London Avenue Canal site (3.53 m versus 3.30 m) after comparing the computed hydrograph made under the wind generated by the Route 2-traveling Hurricane Katrina with the one made under the wind generated by the Route 1-traveling Hurricane Katrina (see the solid red line on Figure 4.67). Therefore, it can be claimed that this evident difference in water surface elevation is caused by a hurricane passing over Lake Pontchartrain with another route although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

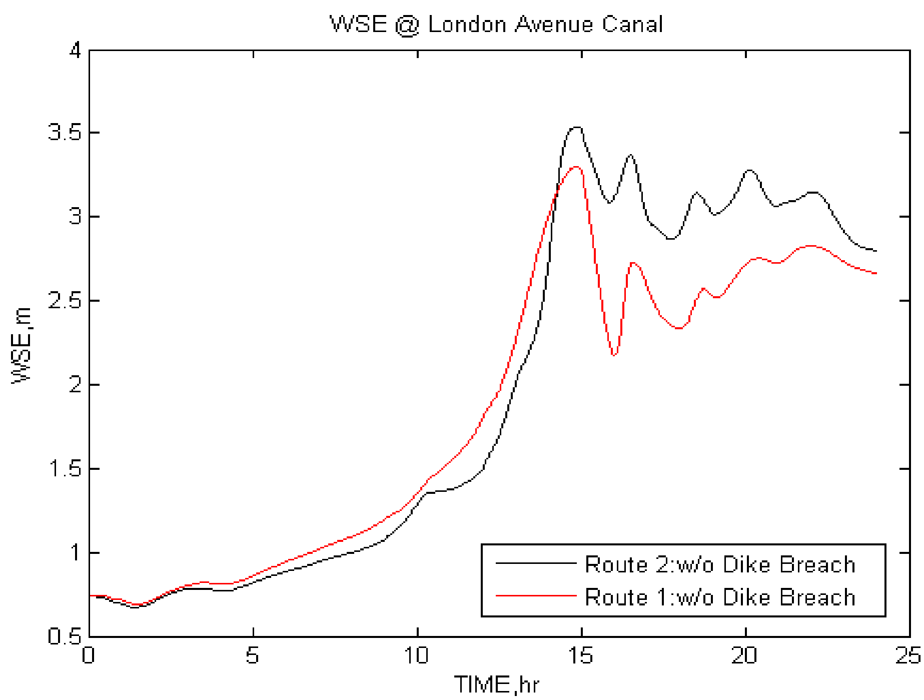

Figure 4.67 Computed Hydrograph, London Avenue Canal

The computed hydrograph (solid black line) obtained from the present model for the IHNC-Lakefront Airport is presented on Figure 4.68. From Figure 4.68, it is seen that the peak water surface elevation (WSE, so called water level in the IPET report) computed by the present model is approximately 3.60 m at the IHNC-Lakefront Airport site. Besides, it is seen that the peak water surface elevation induced by the Route 2-traveling Hurricane Katrina is much higher than the peak water surface level induced by the Route 1-traveling Hurricane Katrina at the IHNC-Lakefront Airport site (3.60 m versus 3.30 m) after comparing the computed hydrograph made under the wind generated by the Route 2-traveling Hurricane Katrina with the one made under the wind generated by the Route 1-traveling Hurricane Katrina (see the solid red line on Figure 4.68). Therefore, it can be claimed that hurricane passing over Lake Pontchartrain with another route can cause an evident difference in water surface elevation although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

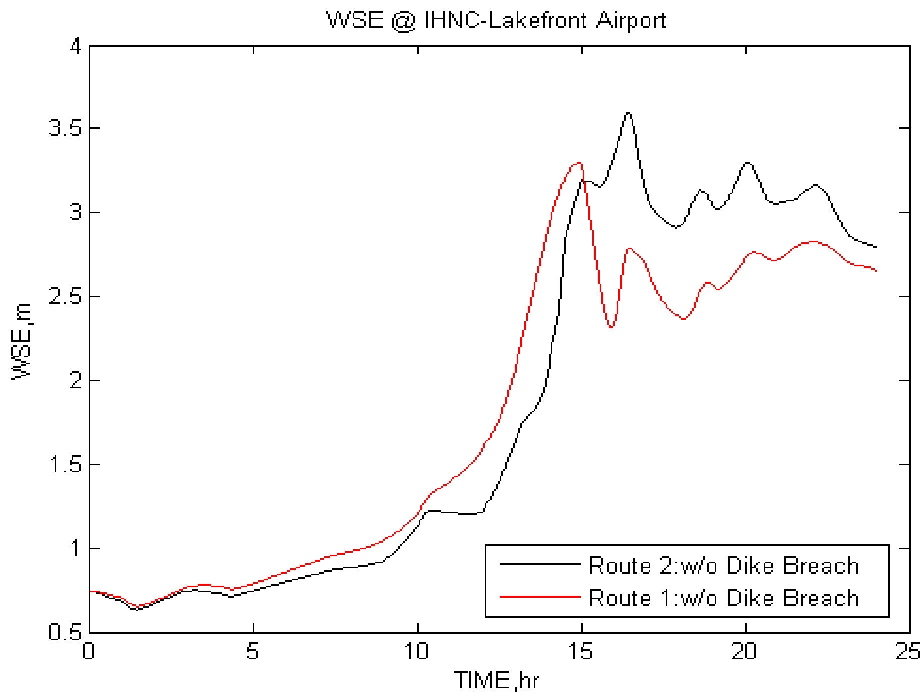

Figure 4.68 Computed Hydrograph, IHNC-Lakefront Airport

The computed hydrograph (solid black line) obtained from the present model for the Midlake is presented on Figure 4.69. From Figure 4.69, it is seen that the peak water surface elevation induced by the Route 2-traveling Hurricane Katrina is much higher than the peak water surface level induced by the Route 1-traveling Hurricane Katrina at the Midlake site after comparing the computed hydrograph made under the wind generated by the Route 2-traveling Hurricane Katrina with the one made under the wind generated by the Route 1-traveling Hurricane Katrina (see the solid red line on Figure 4.69). Furthermore, the general trend of the rise and fall of water level induced by the wind generated by the Route 2-traveling Hurricane Katrina is slightly different from the general trend of the rise and fall of water level induced by the wind generated by the

Route 1-traveling Hurricane Katrina. Therefore, it can be claimed that these evident differences in the water surface elevations are caused by a hurricane passing over Lake Pontchartrain with another route although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

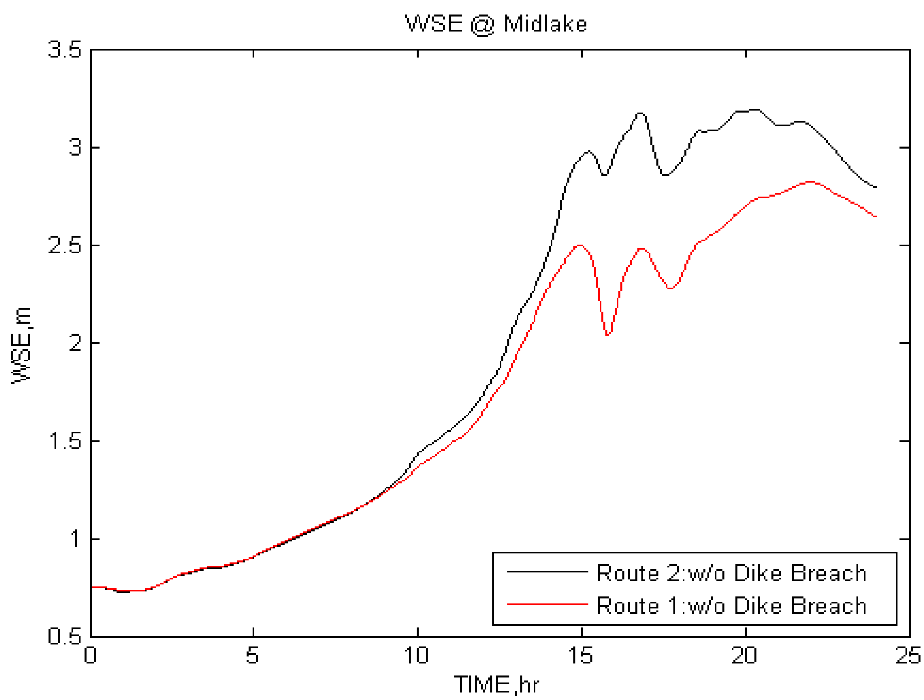

Figure 4.69 Computed Hydrograph, Midlake

The computed hydrograph (solid black line) obtained from the present model for Bayou La Branche (named Bayou Labranch in the IPET report) is presented on Figure 4.70. It can be seen from Figures 4.7 and 4.13 that Bayou La Branche is in the swamp along the southwest shore of Lake Pontchartrain and the swamps along the entire southwest shore of Lake Pontchatrain have been assigned into the computational domain for the current

numerical simulations performed by the present model. From Figure 4.70, it is seen that the peak water surface elevation induced by the Route 2-traveling Hurricane Katrina is much higher than the peak water surface level induced by the original Hurricane Katrina at Bayou La Branche site after comparing the computed hydrograph made under the wind generated by the Route 2-traveling Hurricane Katrina with the one made under the wind generated by the Route 1-traveling Hurricane Katrina (see the solid red line on Figure 4.70). Besides, the general trends of the rise and fall of water levels on both computed hydrographs (solid black and solid red lines on Figure 4.70) made by the present model are almost identical although the highest water surface elevations induced by the winds generated by two hurricanes (Route 2-traveling Katrina and Route 1-traveling Katrina) are significantly different at Bayou La Branche site. Therefore, it can be claimed that this evident difference in the water surface elevation is caused by a hurricane passing over Lake Pontchartrain with another route although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

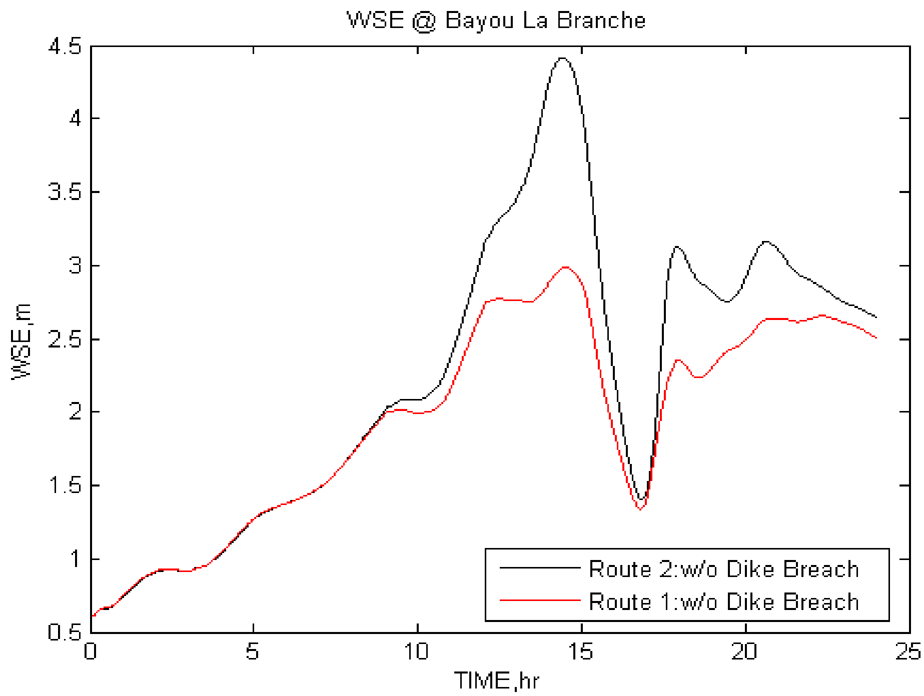

Figure 4.70 Computed Hydrograph, Bayou La Branche

The computed hydrograph (solid black line) obtained from the present model for Pass Manchac-Turtle Cove is presented on Figure 4.71. From Figures 4.7 and 4.13, it can be seen that Pass Manchac is a the narrow strip of water connecting Lake Pontchartrain and Lake Maurepas and the entire Pass Manchac is included in the computational domain used in the current numerical simulations performed by the present model. From Figure 4.71, it is seen that the peak water surface elevation induced by the Route 2-traveling Hurricane Katrina is slightly higher than the peak water surface level induced by the original Hurricane Katrina at Pass Manchac-Turtle Cove site after comparing the computed hydrograph made under the wind generated by the Route 2-traveling Hurricane Katrina with the one made under the wind generated by the Route 1-traveling Hurricane

Katrina (see the solid red line on Figure 4.71). Besides, the general trends of the rise and fall of water levels on both computed hydrographs (solid black and solid red lines on Figure 4.71) made by the present model are almost identical although the highest water surface elevations induced by the winds generated by two hurricanes are different at Pass Manchac-Turtle Cove site. Therefore, it can be claimed that this evident difference in the water surface elevation is caused by a hurricane passing over Lake Pontchartrain-Turtle Cove with another route although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

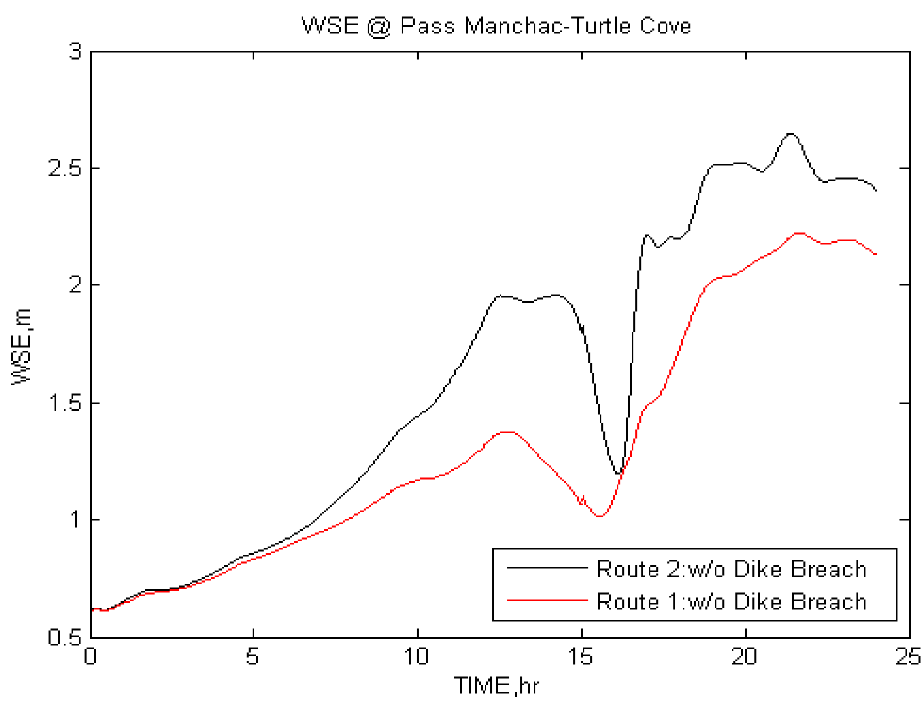

Figure 4.71 Computed Hydrograph, Pass Manchac-Turtle Cove

The computed hydrograph (solid black line) obtained from the present model for Little Irish Bayou is presented on Figure 4.72. From Figure 4.72, it is seen that the peak water surface elevation induced by the Route 2-traveling Hurricane Katrina is much higher than the peak water surface level induced by the Route 1-traveling Hurricane Katrina at Little Irish Bayou site after comparing the computed hydrograph made under the wind generated by the Route 2-traveling Hurricane Katrina with the one made under the wind generated by the Route 1-traveling Hurricane Katrina (see the solid red line on Figure 4.72). Besides, the general trends of the rise and fall of water levels on both computed hydrographs (solid black and solid red lines on Figure 4.72) made by the present model are almost identical although the highest water surface elevations induced by the winds generated by two hurricanes are significantly different at Little Irish Bayou site. Therefore, it can be claimed that this evident difference in the water surface elevation is caused by a hurricane passing over Lake Pontchartrain with another route although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

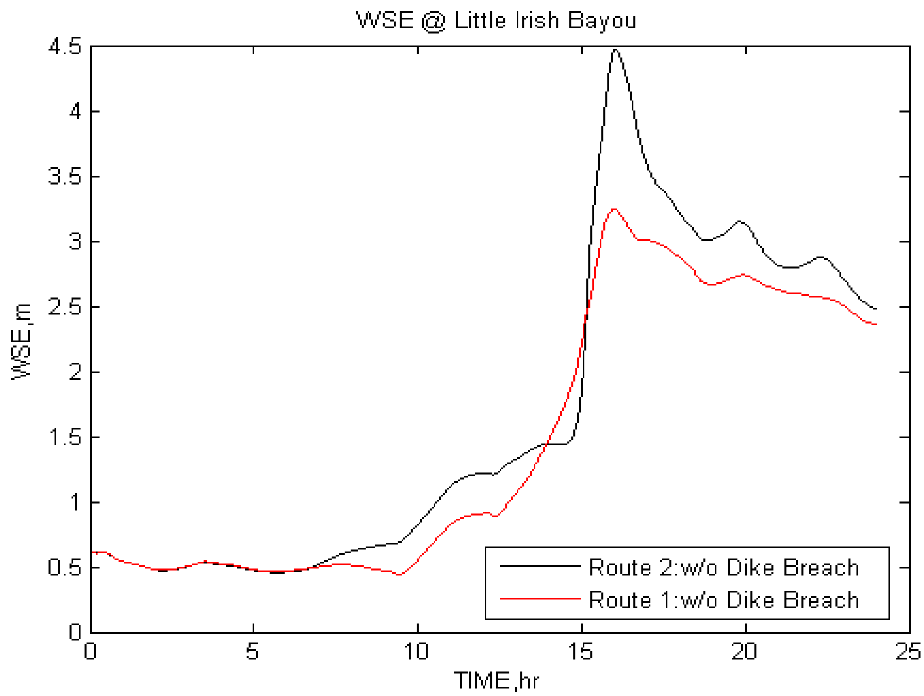

Figure 4.72 Computed Hydrograph, Little Irish Bayou

The computed hydrographs of the water surface elevation (WSE) showing on S-N and W-E cross-sections of Lake Pontchartrain induced by the wind generated through the Route 2-traveling Hurricane Katrina (see Figure 4.28) are presented on Figures 4.73 and 4.74, respectively. It is seen from Figures 4.73 and 4.74 that the wind-induced oscillations in Lake Pontchartrain are the evident phenomena as Hurricane Katrina progressed over the east part of New Orleans, Louisiana (Route 2 shown in Figure 4.28). In the following paragraphs, the hourly contour maps of the water surface elevation (WSE) for the entire Lake Pontchartrain, as Hurricane Katrina progressed over the east part of New Orleans, Louisiana (Route 2 shown in Figure 4.28), ware used to investigate the oscillations of semi-enclosed water body induced by hurricanes under specific routes.

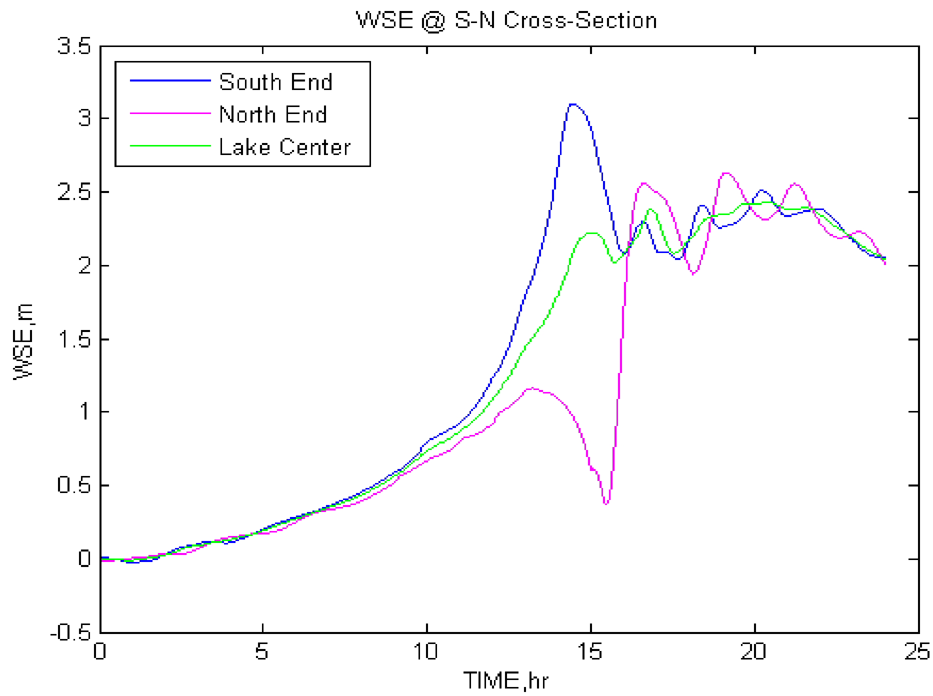

Figure 4.73 Hydrographs of the S-N cross-section

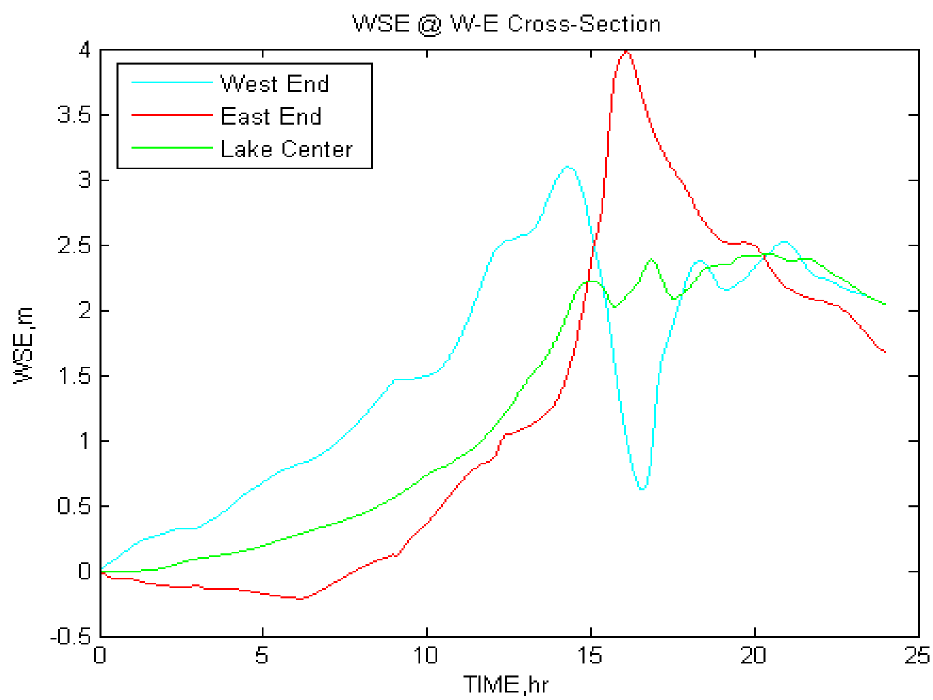

Figure 4.74 Hydrographs of the W-E cross-section

The hourly contour maps of the computed water surface elevation (WSE) for the entire Lake Pontchartrain induced by the wind generated through the Route 2-traveling Hurricane Katrina are presented from Figures 4.75 to Figures 4.99. The time-frame of these contour maps is from 12:00 am UTC August 29, 2005 to 12:00 am UTC August 30, 2005. It is assigned that $t = 0$ is at 11:59:15 pm UTC August 28, 2005 and consequently the reference WSE at $t = 0$ is zero. Therefore, the oscillation phenomenon is not evident throughout entire Lake Pontchartrain at the starting moment of the numerical simulation (12:00 am August 29, 2005), as it is seen from Figure 4.75. As it is seen from Figures 4.2 and 4.28, the original Hurricane Katrina did not make its landfall until 6:10 am CDT (11:10 am UTC) August 29 at Southeast Louisiana and the distance between the Route 1 and Route 2 is approximately 36 km; besides, the oscillation induced by tides from Gulf of Mexico into Lake Pontchartrain is not influential in this study, this is a reasonable assumption that the oscillations in Lake Pontchartrain induced by wind generated by the Route 2-traveling Hurricane Katrina can be focused on the 24-hours period between 12:00 am UTC August 29, 2005 and 12:00 am UTC August 30, 2005.

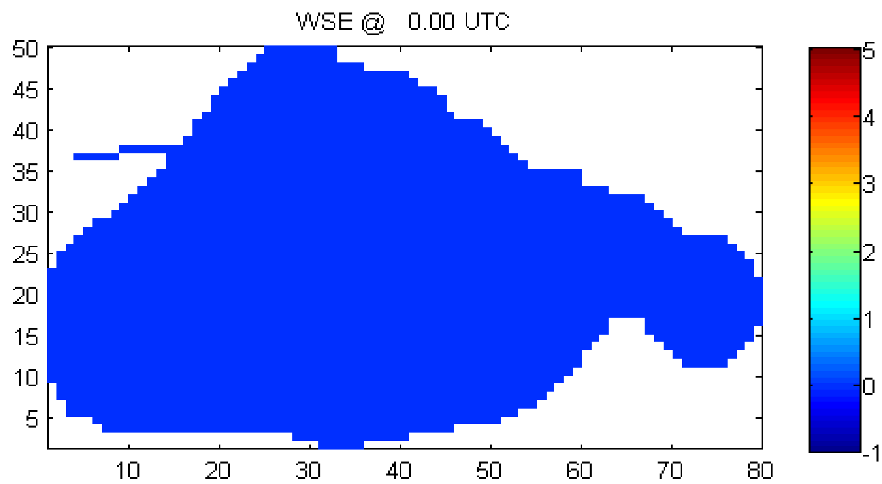

Figure 4.75 Contours of WSE at 12:00 am (UTC) August 29, 2005

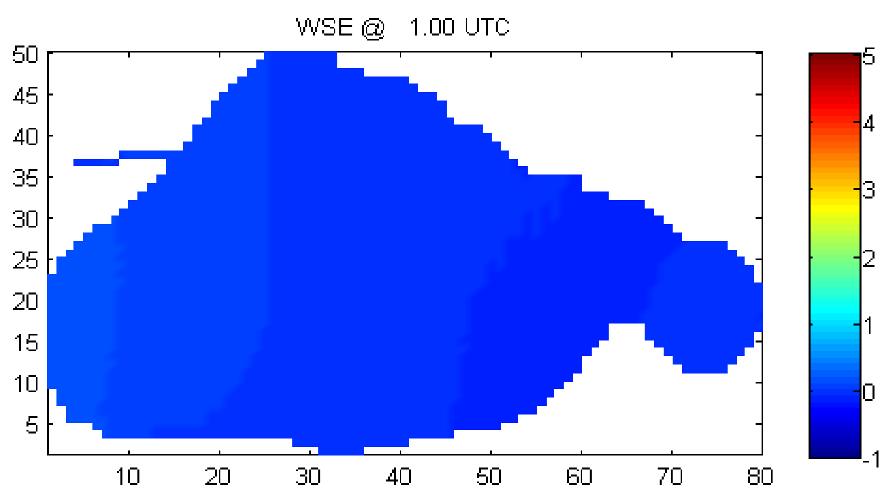

Figure 4.76 Contours of WSE at 01:00 am (UTC) August 29, 2005

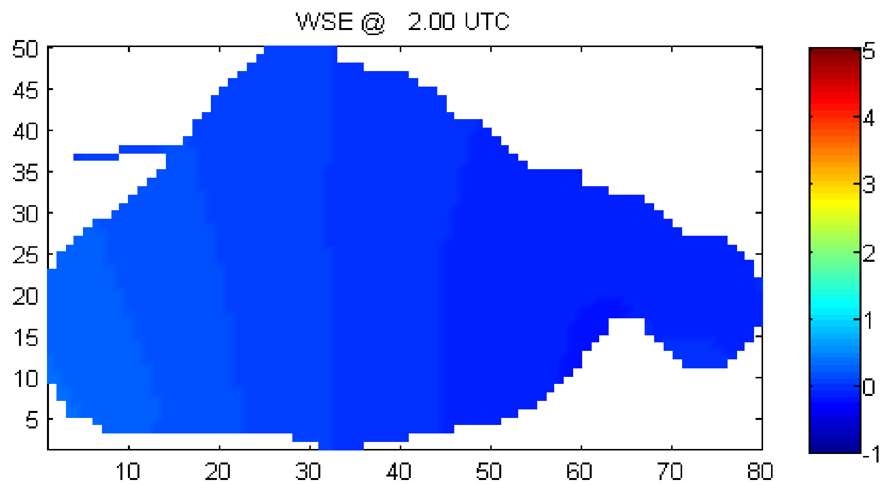

Figure 4.77 Contours of WSE at 02:00 am (UTC) August 29, 2005

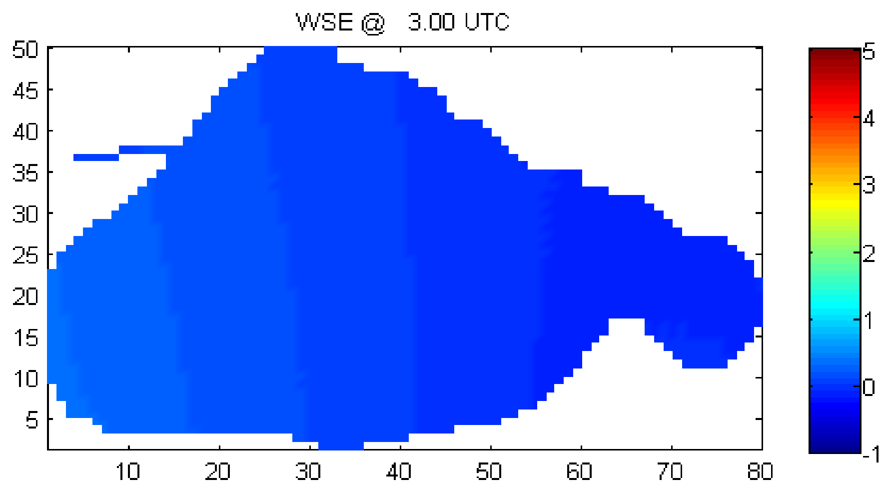

Figure 4.78 Contours of WSE at 03:00 am (UTC) August 29, 2005

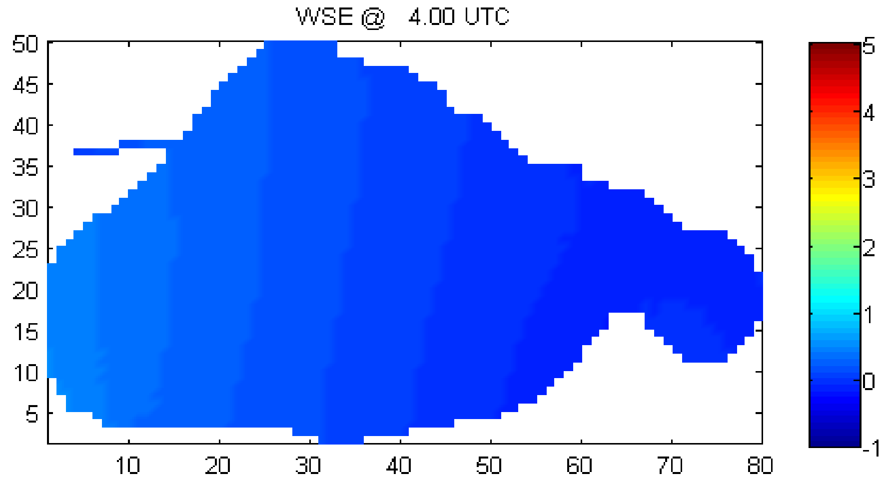

Figure 4.79 Contours of WSE at 04:00 am (UTC) August 29, 2005

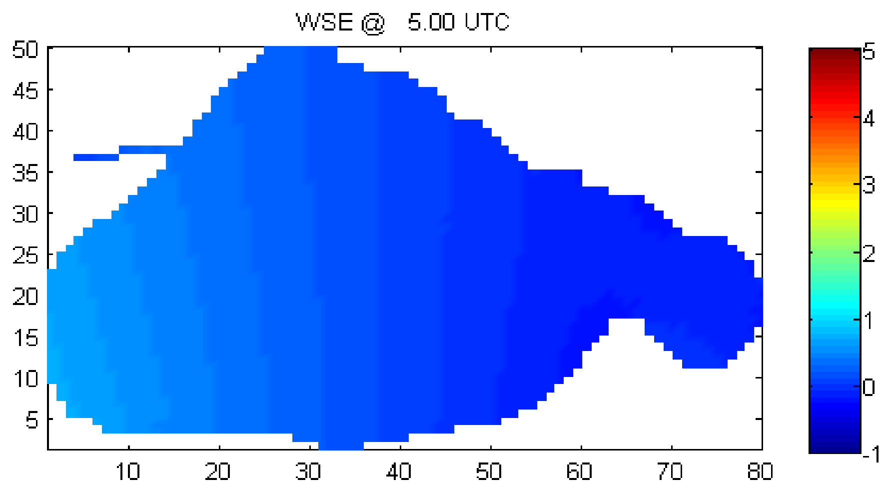

Figure 4.80 Contours of WSE at 05:00 am (UTC) August 29, 2005

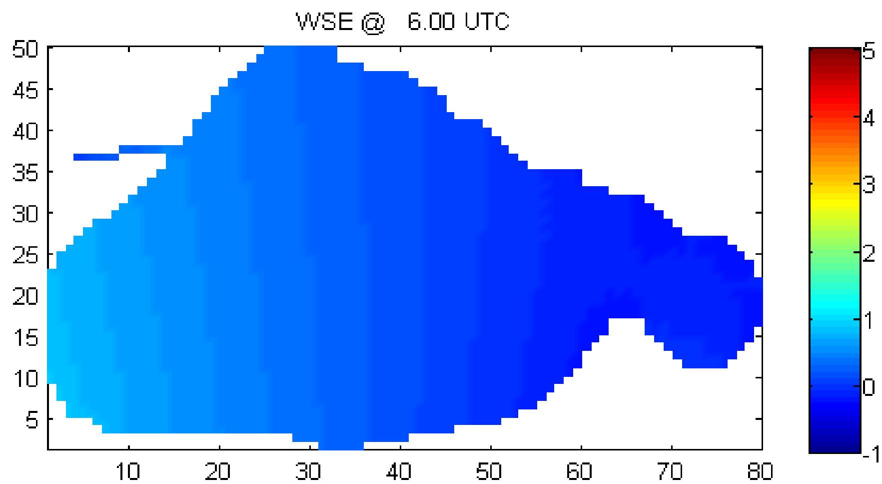

Figure 4.81 Contours of WSE at 06:00 am (UTC) August 29, 2005

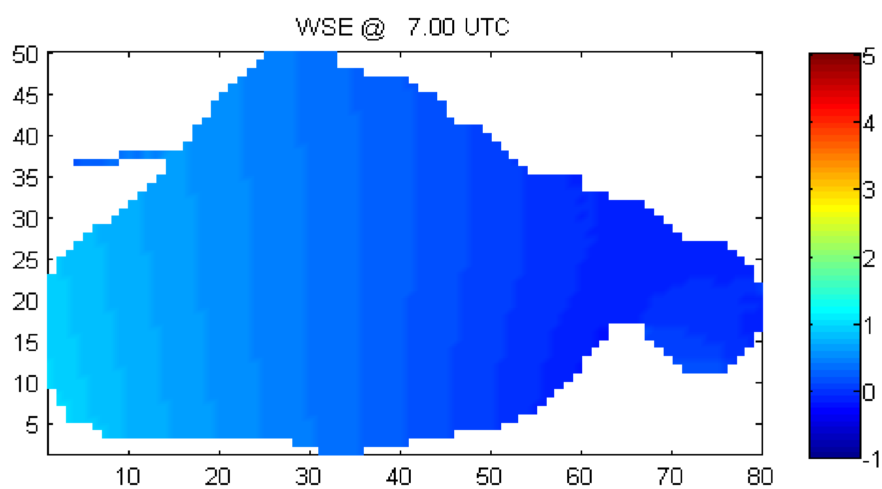

Figure 4.82 Contours of WSE at 07:00 am (UTC) August 29, 2005

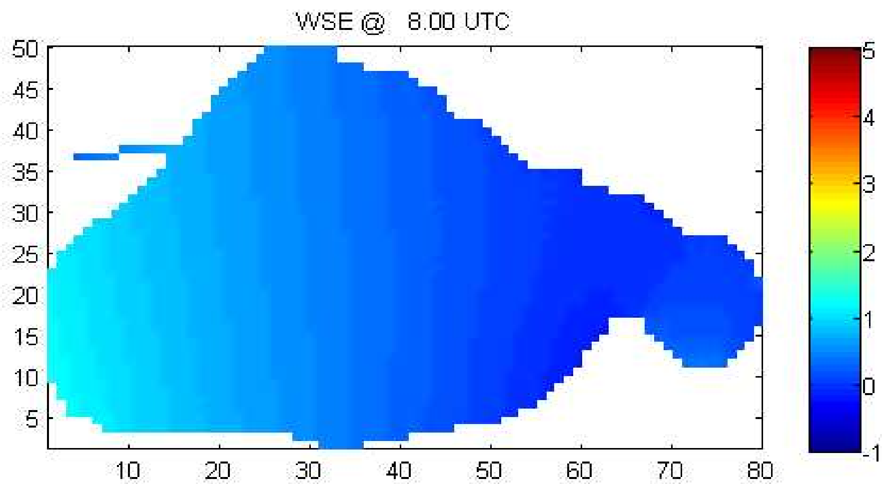

Figure 4.83 Contours of WSE at 08:00 am (UTC) August 29, 2005

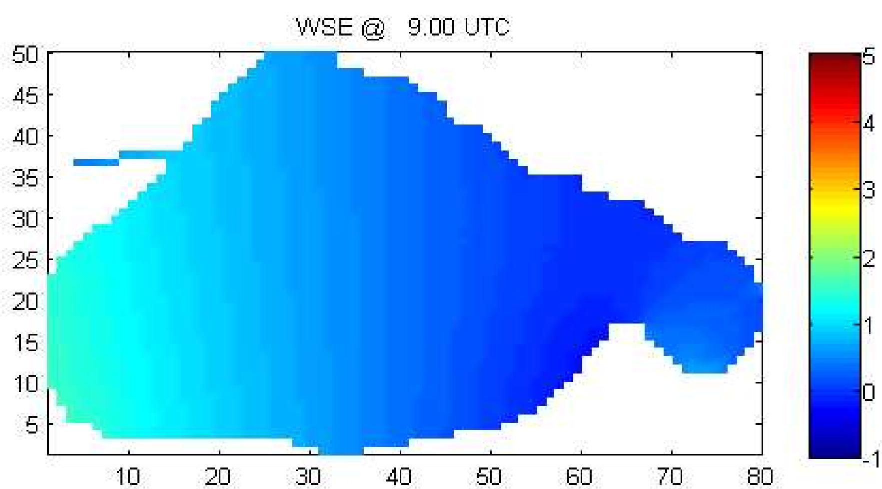

Figure 4.84 Contours of WSE at 09:00 am (UTC) August 29, 2005

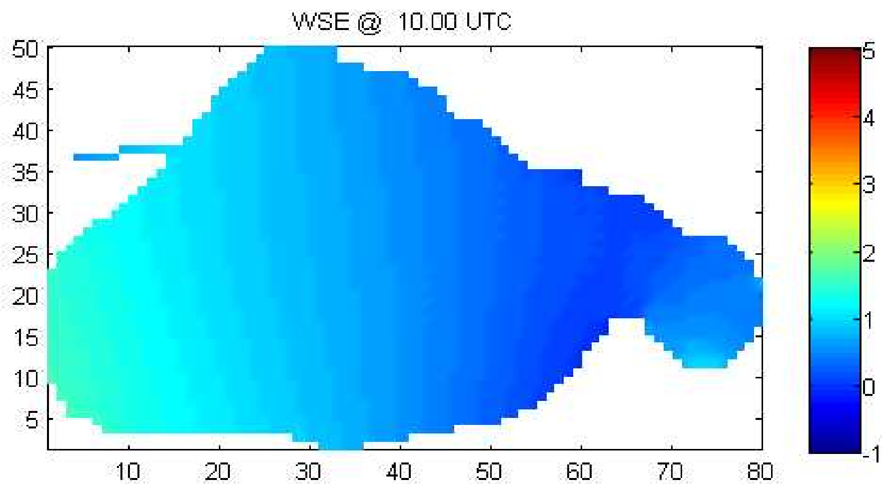

Figure 4.85 Contours of WSE at 10:00 am (UTC) August 29, 2005

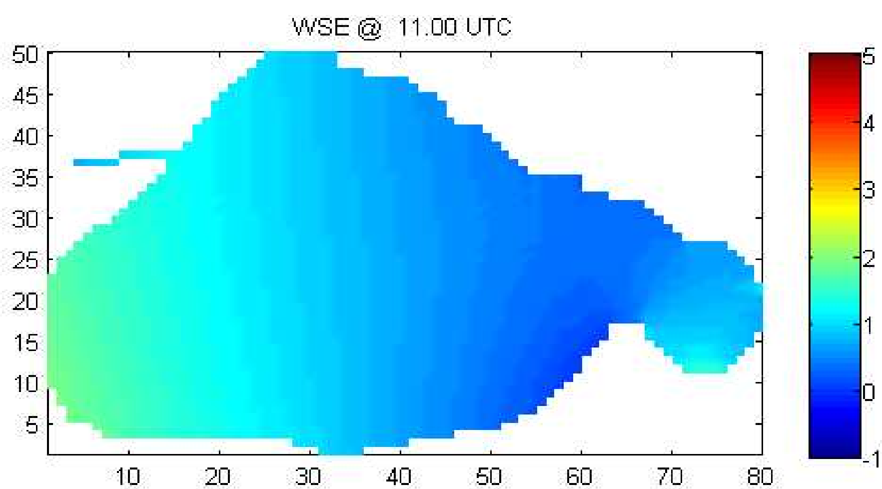

Figure 4.86 Contours of WSE at 11:00 am (UTC) August 29, 2005

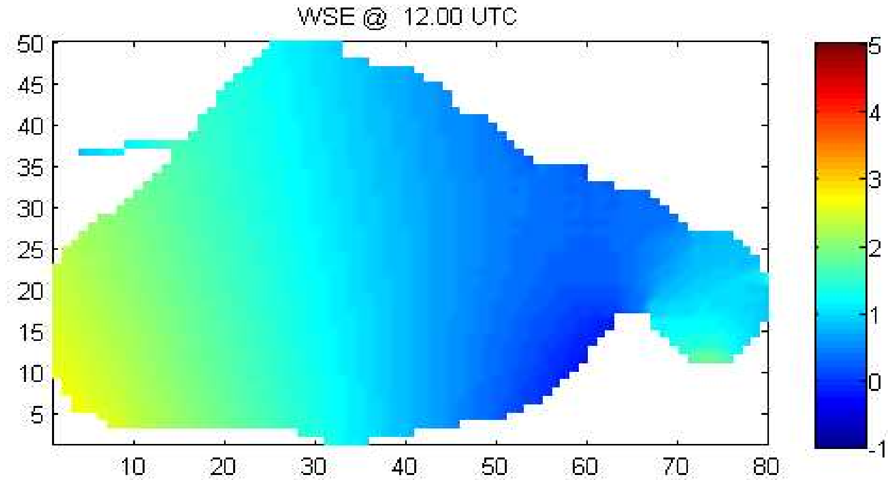

Figure 4.87 Contours of WSE at 12:00 pm (UTC) August 29, 2005

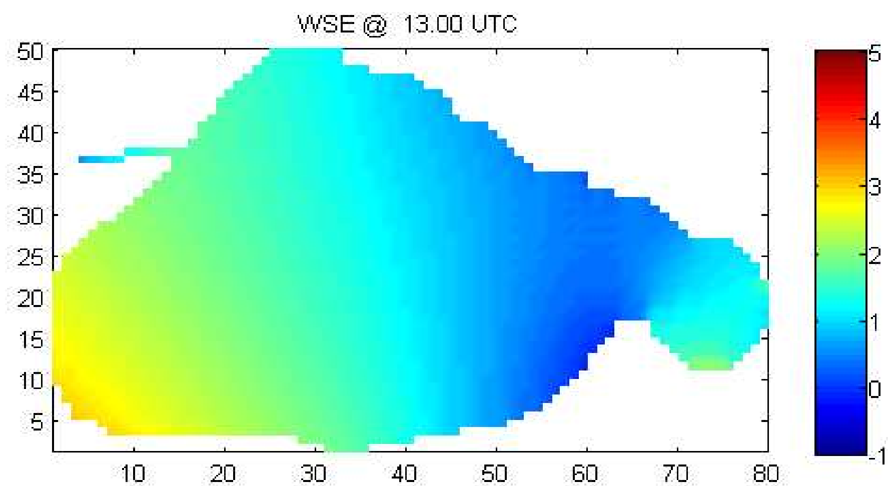

Figure 4.88 Contours of WSE at 01:00 pm (UTC) August 29, 2005

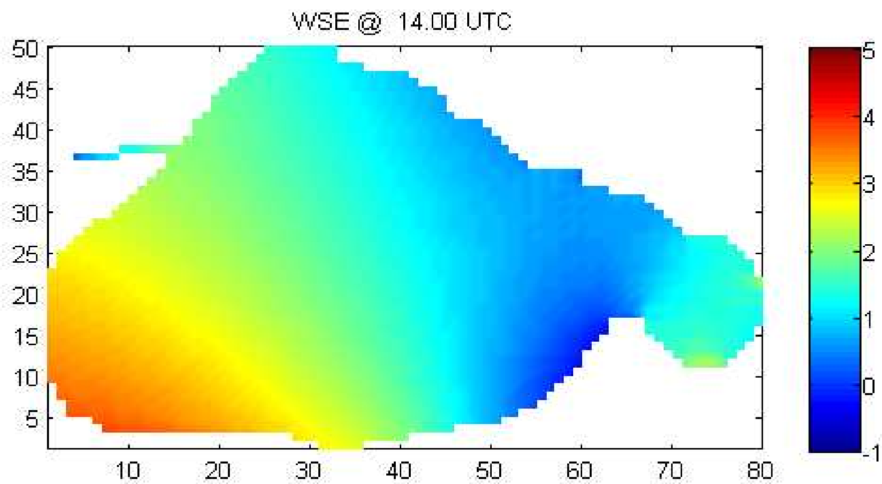

Figure 4.89 Contours of WSE at 02:00 pm (UTC) August 29, 2005

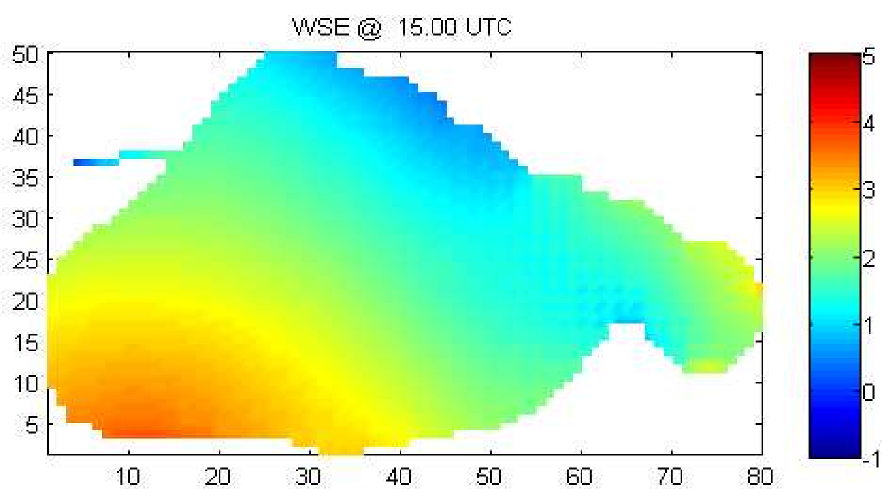

Figure 4.90 Contours of WSE at 03:00 pm (UTC) August 29, 2005

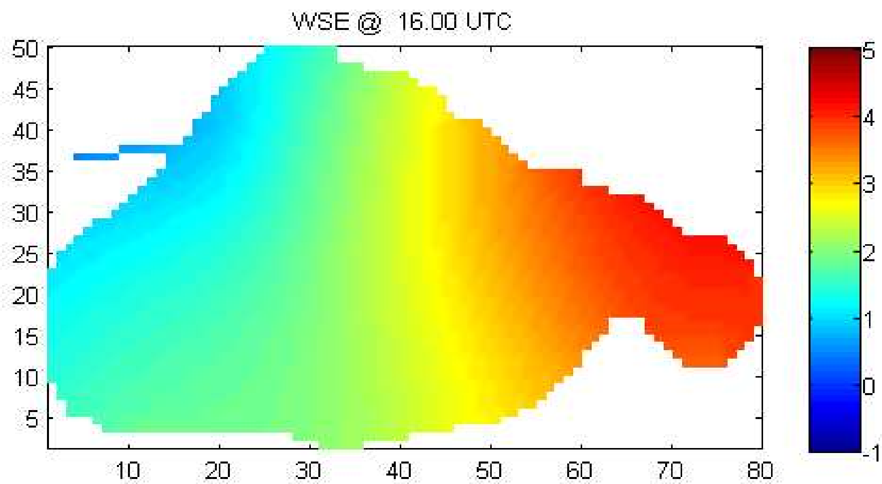

Figure 4.91 Contours of WSE at 04:00 pm (UTC) August 29, 2005

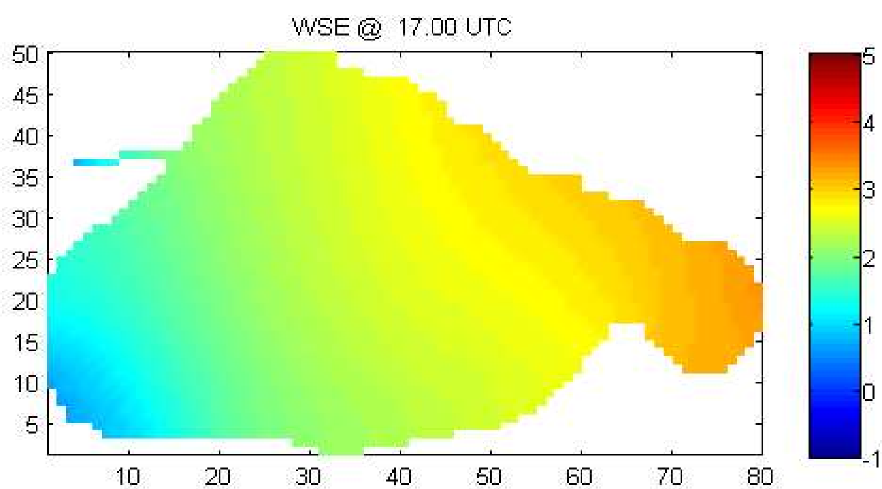

Figure 4.92 Contours of WSE at 05:00 pm (UTC) August 29, 2005

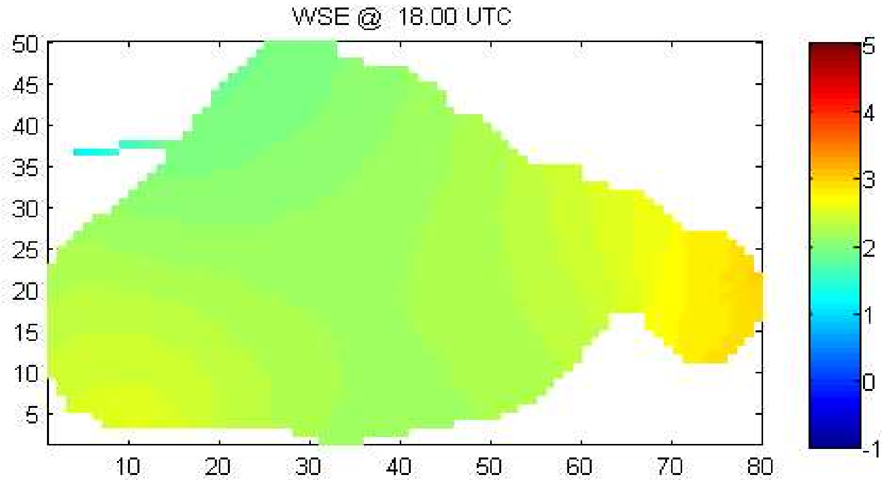

Figure 4.93 Contours of WSE at 06:00 pm (UTC) August 29, 2005

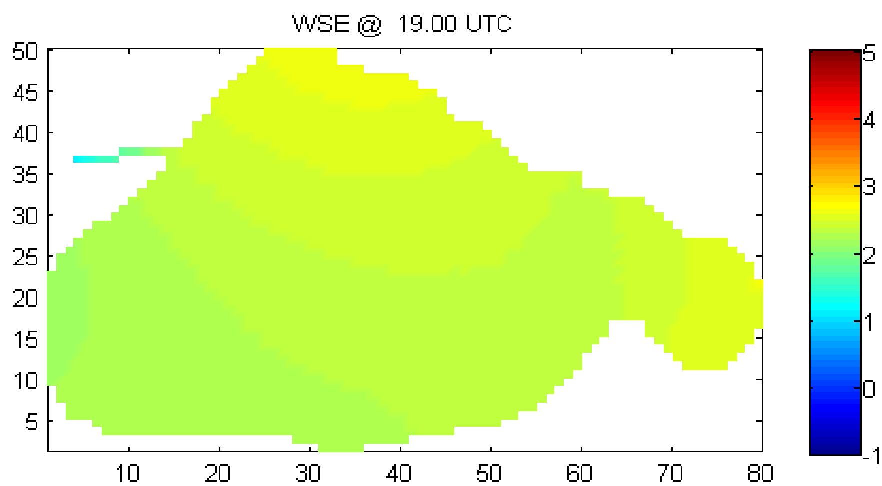

Figure 4.94 Contours of WSE at 07:00 pm (UTC) August 29, 2005

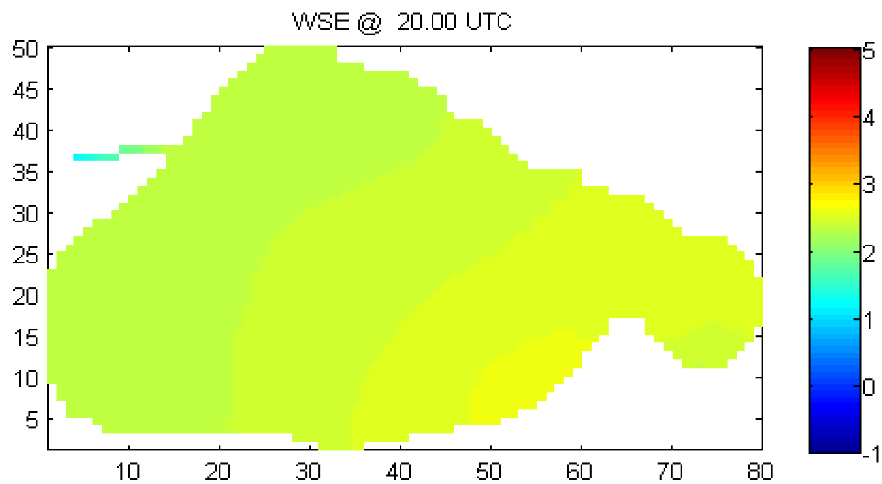

Figure 4.95 Contours of WSE at 08:00 pm (UTC) August 29, 2005

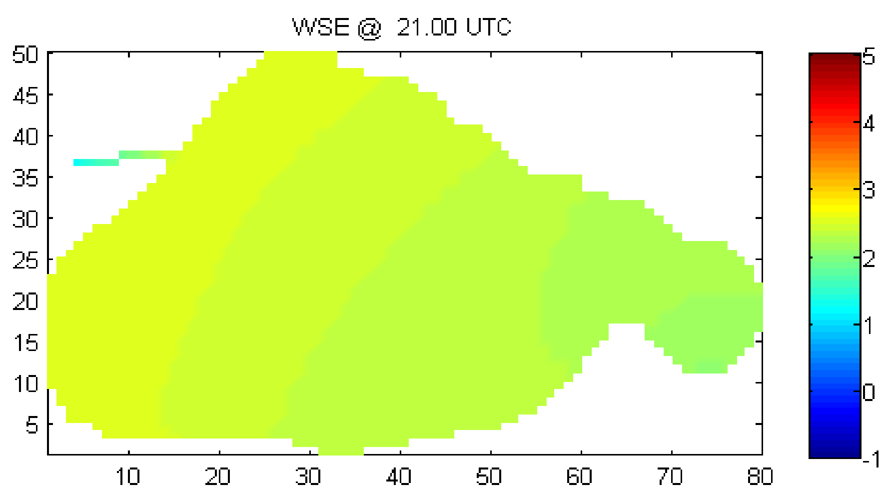

Figure 4.96 Contours of WSE at 09:00 pm (UTC) August 29, 2005

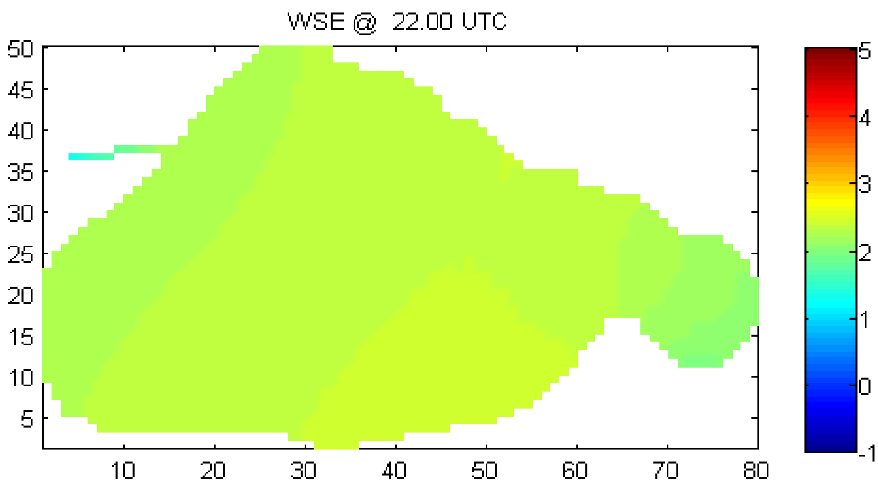

Figure 4.97 Contours of WSE at 10:00 pm (UTC) August 29, 2005

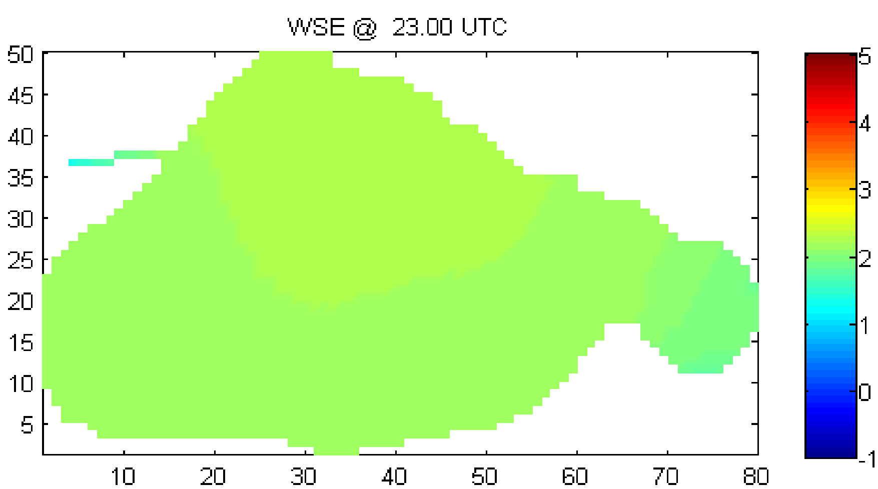

Figure 4.98 Contours of WSE at 11:00 pm (UTC) August 29, 2005

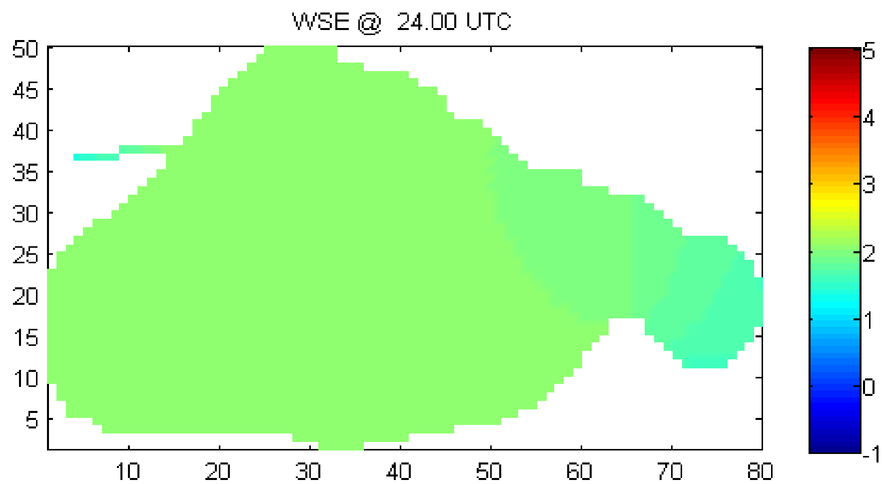

Figure 4.99 Contours of WSE at 12:00 am (UTC) August 30, 2005

It can be seen from Figures 4.76 to 4.84 that the oscillation in Lake Pontchartrain is built up as Hurricane Katrina approaches to Southeast Louisiana and it becomes more obvious as time goes by. It is very evident that the direction of node line ($\eta = 0$) in the lake is in the North-South orientation. Besides, it is possible that the Route 2-traveling Hurricane Katrina makes its landfall at Southeast Louisiana around 11:00 am UTC (6:00 am Local Time) August 29 since the distance between Route 1 and Route 2 is about only 36 km (see Figures 4.2 and 4.28). It is seen that the water in the east part of the lake is driven by the wind to the west part of the lake during the first 9-hour period, as we examine the temporal variations of the contours of WSE from 12:00 to 09:00 am UTC August 29,

2005. The strength of Hurricane Katrina, according to the IPET report, is gradually reducing from Category 4 to 3 in Saffir-Simpson Scale within this 9-hours period. As the Route 2-traveling Hurricane Katrina approaches Southeast Louisiana, the magnitude of oscillation in the lake gradually increases between 09:00 am UTC and 12:00 pm UTC August 29, 2005. During this 3-hours period, the direction of node line ($\eta = 0$) in the lake changes from the North-South orientation to the slightly Northwest-Southeast orientation since the direction of the dominant wind alters as Hurricane Katrina approaches to Lake Pontchartrain while its strength remains Category 3. We can see these phenomena after examining the temporal variations of the contours of WSE from Figures 4.85 to 4.87.

From 12:00 pm UTC to 03:00 pm UTC August 29, the Route 2-traveling Hurricane Katrina passes over the east part of New Orleans, Louisiana, and the south-central part of Lake Pontchartrain. Thus, this close-encounter between the hurricane and the lake causes significant oscillations in Lake Pontchartrain as we compare the oscillations happened in the lake during the previous 12 hours. It is seen from Figures 4.88 to 4.90 that the direction of node line ($\eta = 0$) in the lake changes from the slightly Northwest-Southeast orientation to the nearly West-East orientation as the direction of the dominant wind rapidly alters during this 3-hours period. Meanwhile, the magnitude of oscillation (the height of WSE) becomes higher than the previous 3 hours, and the oscillation along the southeast and south shores of Lake Pontchartrain reaches the highest magnitude between 02:30 and 03:00 pm UTC (or 09:30 and 10:00 am Local Time), as we have already seen from Figures 4.65 to 4.88. Within this 3-hours period, the strength of the Route 2-traveling Hurricane Katrina still remains Category 3.

During the next 3-hours period (from 03:00 to 06:00 pm UTC August 29), the Route 2-traveling Hurricane Katrina continuously crosses over Lake Pontchartrain and moves inland with a nearly north direction while its strength reduces from Category 3 to 2. Meanwhile, the direction of node line ($\eta = 0$) rapidly turns from the nearly West-East orientation to the nearly South-North orientation as the direction of the dominant wind alters 90° in a counterclockwise pattern even though the wind generated by the hurricane gets weaker during this 3-hours time-period. Because the surge propagates into Lake Pontchartrain from the Gulf of Mexico via Lake Borgne (see Figure 4.3), a huge amount of water flows into Lake Pontchartrain and the magnitude of oscillation (the height of WSE) in Lake Pontchartrain evidently increases even though the hurricane leaves the central and northeast regions of the lake. Furthermore, the node line ($\eta = 0$) disappears and the WSE in the entire lake is greater than the reference WSE ($\eta = 0$) from 06:00 pm, as it is seen from Figure 4.93. We can find these evidences from a thorough study of the temporal variations of the contours of WSE from Figures 4.91 to 4.93.

In the final 6-hours period (from 07:00 pm UTC August 29 to 12:00 am UTC August 30, 2005), the strength of the Route 2-traveling Hurricane Katrina continuously reduces from Category 2 to 1; furthermore, the Route 2-traveling Hurricane Katrina becomes a tropical storm as it moves inwardly into the northeastern region of the United States of America as the original Hurricane Katrina moves inwardly (see Figures 4.2 and 4.28). Although the direction of dominant wind keeps turning counterclockwise during this 6-hours period, the wind generated by the hurricane is drastically weaker than it was in the previous 18-hours period. Since the hurricane moves far away from the lake, the magnitude of oscillation in Lake Pontchartrain gradually reduces and is smaller than it was in the previous 6-hour period. Besides, the major sloshing motion is moving toward the east within this 6-hours period. The WSE in the lake does not significantly recede since there is not enough wind stress to drive out the water from Lake Pontchartrain to Lake Borgne and other surrounding water bodies (for example, Lake Maurepas); hence, the WSE in the entire lake is greater than the reference WSE ($\eta = 0$) in this 6-hours period. Meanwhile, there is a significant drawdown in the east portion of Lake Pontchartrain at the finale of the numerical simulation (10:00 pm August 29 to 12:00 am August 30, 2005) as it is seen from Figures 4.84 to 4.86. We can obtain these discoveries by examining the temporal variations of WSE from Figures 4.94 to 4.99. Furthermore, the significant findings drawn from these hourly contour maps (from Figures 4.75 to 4.99) are summarized in the following paragraphs.

The Route 2-traveling Hurricane Katrina moves in a nearly north direction and passes over the east part of New Orleans, Louisiana and the central and east parts of Lake Pontchartrain between 12:00 am and 06:00 pm UTC August 29, 2005 corresponding to the first 18-hours of the numerical simulations made by the present model. The closest encounter between Hurricane Katrina and Lake Pontchartrain takes place between 12:00 and 06:00 pm UTC (or 7:00 am and 1:00 pm Local Time) August 29, 2005 (see Figure 4.2). During this 6-hours period, there are three significant factors of Hurricane Katrina needed to be reviewed:

1. The hurricane remains Category 3 intensity of Saffir-Simpson Scale until 03:00 pm UTC (10:00 am Local Time), after which the strength of the hurricane gradually reduces to Category 2.
2. The hurricane is moving in a nearly north direction with an approximate speed of 27 to 29 km/hr.
3. The eye of the Route 2-traveling Hurricane Katrina passes through the south and southwest shores of Lake Pontchartrain.

Because of these three unique characteristics of the interaction between the hurricane and the lake, the sloshing motion of the lake water surface changes in a counterclockwise pattern in the lake as the hurricane itself rotates in the counterclockwise character. In detail, the dominant sloshing motion at Lake Pontchartrain turns from the slightly southwest to the east within this 6-hours period. During this 6-hours, the highest amplitude of oscillation (maximum WSE) along the south shore of the lake happens between 02:30 and 03:00 pm UTC (between 09:30 and 10:00 am Local Time) with a magnitude of 3.53 m to 3.86 m predicted by the newly developed finite-volume method (FVM) model.

Furthermore, the moving direction of the storm surge changes from the west direction to the east direction within the first 16-hours period (12:00 am to 04:00 pm UTC August 29, 2005) of the numerical simulations (see Figures 4.75 to 91); in other words, the sloshing motion changes 180° in 16 hours. Therefore, the oscillation (rise and fall of water level) in a semi-enclosed lake induced by a hurricane will be moving around the lake in a counterclockwise-turning pattern whenever a hurricane either passes through the regions along the east shore or pass over the central part of the lake. While a hurricane circulates counterclockwise and the direction of the accompanying wind generated by the hurricane turns in a counterclockwise pattern, the magnitude of oscillation thoroughly depends on the strength (wind speed) and the duration (length in time) of the wind to a specific direction. In other words, the magnitude of the oscillation (height of rise and fall) associated with the moving direction will be different at each specific location around the lake.

4.5.3 Hurricane Katrina Traveling Along Route 3

The present model is used to study the oscillation in Lake Pontchartrain induced by wind generated by the Route 3-traveling Hurricane Katrina (see Figure 4.28). The dimensions of the uniform rectangular control-volumes (CV's) in a Cartesian grid are $(\Delta x, \Delta y) = (750\,m, 750\,m)$. The time-step Δt is chosen to be 45 seconds. The bathymetry of Lake Pontchartrain adopted from the Interagency Performance Evaluation Task Force

(IPET) report is used in the numerical simulations (see Figure 4.14). The time-period in the numerical simulations for the oscillation in Lake Pontchartrain induced by wind generated by the Route 3-traveling Hurricane Katrina is from 12:00 am UTC (Coordinated Universal Time) August 29, 2005 to 12:00 am UTC August 30, 2005, or 07:00 pm CDT (Central Daylight Time) August 28, 2005 to 07:00 pm CDT August 29, 2005. During this 24-hours time-period, Hurricane Katrina will make its landfall at Southeast Louisiana and will pass over the west shore and its surround regions of Lake Pontchartrain (see Figures 4.2 and 4.28). Hence, the study of the oscillation in Lake Pontchartrain induced by wind generated by the Route 3-traveling Hurricane Katrina can be concentrated in this 24-hours period. In order to study the oscillation phenomena in Lake Pontchartrain induced by the Route-3 traveling Hurricane Katrina, the breaches and/or overtopping of floodwalls and levees along Lake Pontchartrain will not be accommodated into the numerical simulations performed by the present model for this case; hence, the water can not flow out of the lake through the entrances of the canals connecting to the lake during the entire 24-hours period of the numerical simulations for the oscillations of Lake Pontchartrain induced by the Route-3 traveling Hurricane Katrina.

The wind field inducing the oscillations in Lake Pontchartrain is exclusively caused by the Route 3-traveling Hurricane Katrina. The numerical typhoon (or hurricane) model, based on Equation (3.9) through Equation (3.14) in Chapter 3 and developed along with the present model in this study, is used to generate the pressure and wind fields. The meteorological data to simulate Hurricane Katrina between 12:00 am UTC August 29, 2005 and 12:00 am UTC August 30, 2005 are adopted from the Interagency Performance Evaluation Task Force (IPET) report and are listed in Table 4.1. The diameters of the eye of the simulated Hurricane Katrina by the numerical hurricane model are the distances corresponding to a time interval of a half-hour traveling of the simulated Hurricane Katrina. The speeds for the simulated Hurricane Katrina derived from the moving path of Hurricane Katrina between 12:00 am UTC August 29, 2005 and 12:00 am UTC August 30, 2005 are interpreted from the hourly Latitudes and Longitudes of Hurricane Katrina recorded in the Interagency Performance Evaluation Task Force (IPET) report.

The computed hydrograph (solid black line) obtained from the present model for the 17th Street Canal is presented on Figure 4.100. From Figure 4.100, it is seen that the peak water surface elevation (WSE, so called water level in the IPET report) computed by the present model is approximately 3.11 m at the 17th Street Canal site. In addition, it is seen that an abrupt fall and rise of water level (2.73 m) within 2 hours is computed by the present model at the 17th Street Canal site; in other words, this sudden change of water surface elevation (WSE) can caused a severe damage to the ships mooring around the entrance of the 17th Street Canal. Furthermore, it is seen that the peak water surface elevation induced by the Route 3-traveling Hurricane Katrina is lower than the peak water surface level induced by the Route 1-traveling Hurricane Katrina at the 17th Street Canal site (3.11 m versus 3.30 m) after comparing the computed hydrograph made under the wind generated by the Route 3-traveling Hurricane Katrina with the one made under the wind generated by the Route 1-traveling Hurricane Katrina (see the solid red line on Figure 4.100); besides, the general trend of the fall and rise of water level induced by the wind generated by the Route 3-traveling Hurricane Katrina is entirely different from the general trend of the rise and fall of water level induced by the wind generated by the Route 1-traveling Hurricane Katrina. Therefore, it can be claimed that these evident differences in water surface elevation is caused by a hurricane passing over Lake Pontchartrain with another route although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

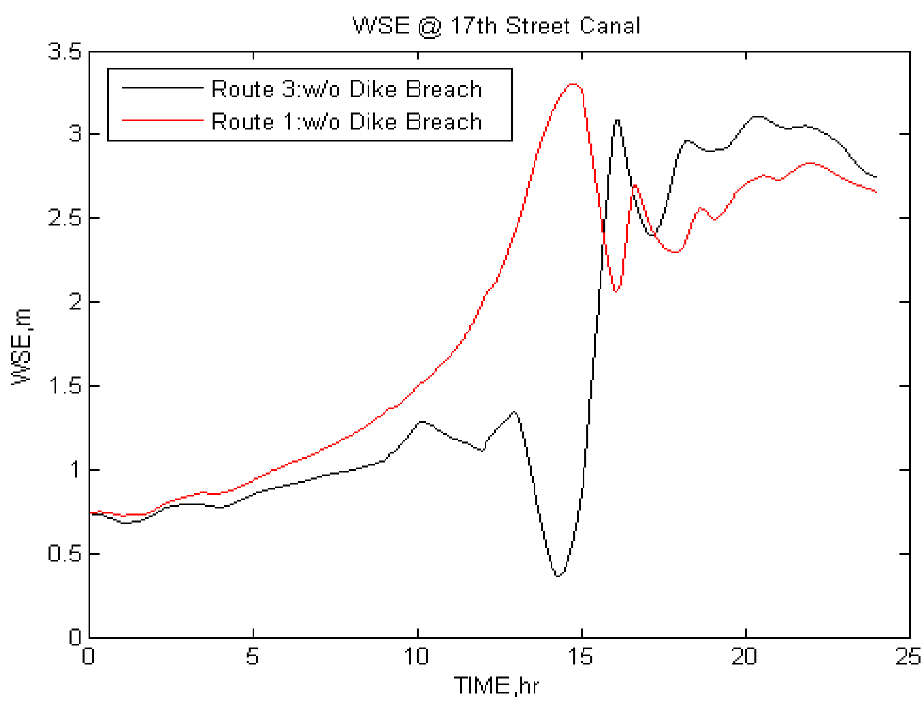

Figure 4.100 Computed Hydrograph, 17th Street Canal

The computed hydrograph (solid black line) obtained from the present model for the Orleans Avenue Canal is presented on Figure 4.101. From Figure 4.101, it is seen that the peak water surface elevation (WSE, so called water level in the IPET report) computed by the present model is approximately 3.19 m at the Orleans Avenue Canal site. In addition, it is seen that an abrupt fall and rise of water level (2.89 m) within 2 hours is computed by the present model at the Orleans Avenue Canal site; in other words, this sudden change of water surface elevation (WSE) can caused a severe damage to the ships mooring around the entrance of the Orleans Avenue Canal. Furthermore, it is seen that the peak water surface elevation induced by the Route 3-traveling Hurricane Katrina is lower than the peak water surface level induced by the Route 1-traveling Hurricane Katrina at the Orleans Avenue Canal site (3.19 m versus 3.27 m) after comparing the computed hydrograph made under the wind generated by the Route 3-traveling Hurricane Katrina with the one made under the wind generated by the Route 1-traveing Hurricane Katrina (see the solid red line on Figure 4.101); besides, the general trend of the fall and rise of water level induced by the wind generated by the Route 3-traveling Hurricane Katrina is entirely different from the general trend of the rise and fall of water level induced by the wind generated by the Route 1-traveling Hurricane Katrina. Therefore, it can be claimed that hurricane passing over Lake Pontchartrain with another route can cause evident differences in water surface elevation although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

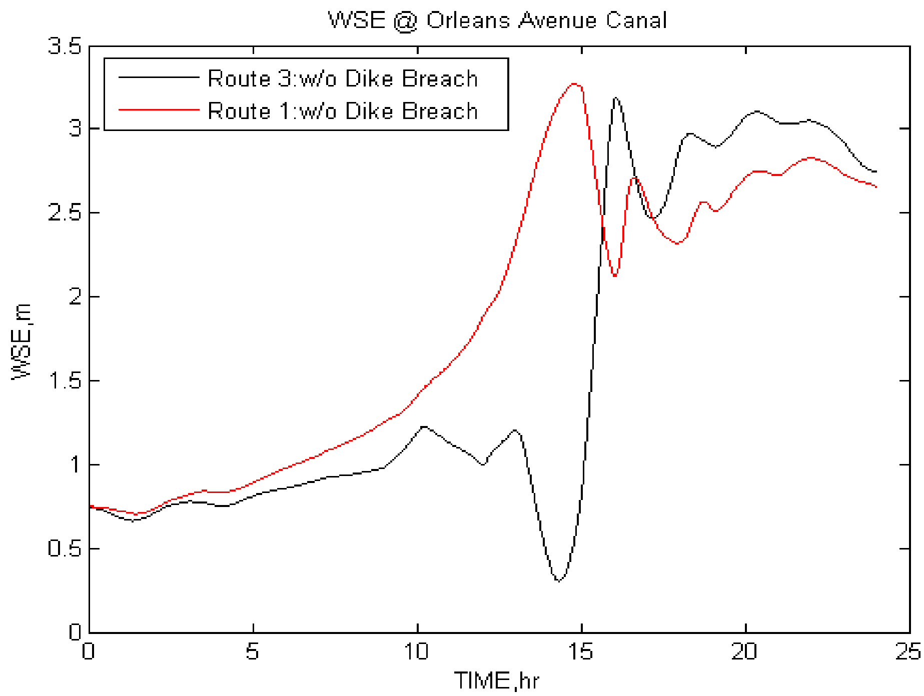

Figure 4.101 Computed Hydrograph, Orleans Avenue Canal

The computed hydrograph (solid black line) obtained from the present model for the London Avenue Canal is presented on Figure 4.102. From Figure 4.102, it is seen that the peak water surface elevation (WSE, so called water level in the IPET report) computed by the present model is approximately 3.23 m at the London Avenue Canal site. In addition, it is seen that an abrupt fall and rise of water level (2.97 m) within 2 hours is computed by the present model at the London Avenue Canal site; in other words, this sudden change of water surface elevation (WSE) can caused a severe damage to the ships mooring around the entrance of the London Avenue Canal. Furthermore, it is seen that the peak water surface elevation induced by the Route 3-traveling Hurricane Katrina is lower than the peak water surface level induced by the Route 1-traveling Hurricane

Katrina at the London Avenue Canal site (3.23 m versus 3.30 m) after comparing the computed hydrograph made under the wind generated by the Route 3-traveling Hurricane Katrina with the one made under the wind generated by the original Hurricane Katrina (see the solid red line on Figure 4.102); besides, the general trend of the fall and rise of water level induced by the wind generated by the Route 3-traveling Hurricane Katrina is entirely different from the general trend of the rise and fall of water level induced by the wind generated by the Route 1-traveling Hurricane Katrina. Therefore, it can be claimed that these evident differences in water surface elevation is caused by a hurricane passing over Lake Pontchartrain with another route although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

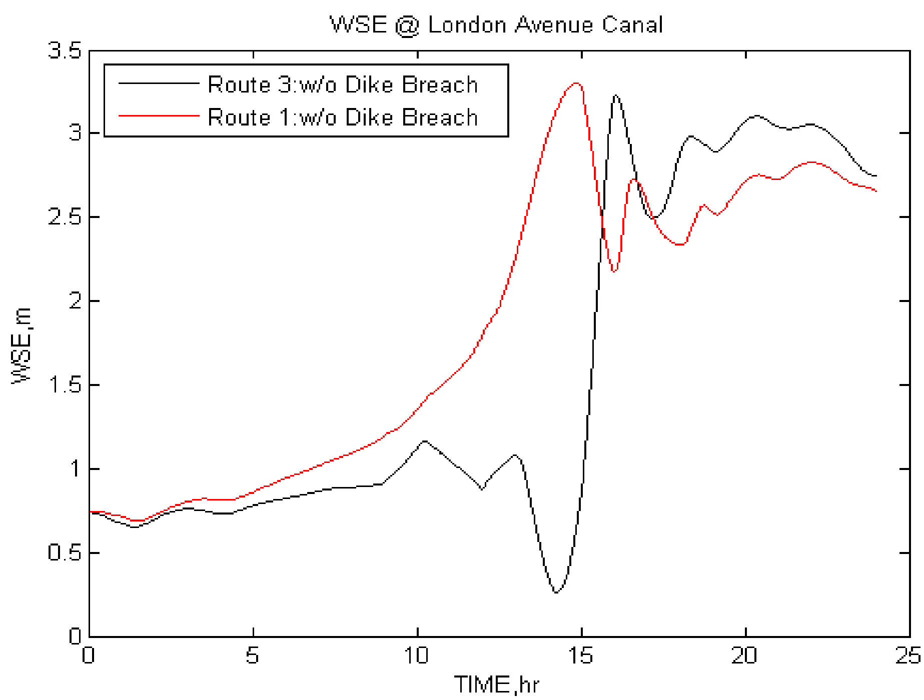

Figure 4.102 Computed Hydrograph, London Avenue Canal

The computed hydrograph (solid black line) obtained from the present model for the IHNC-Lakefront Airport is presented on Figure 4.103. From Figure 4.103, it is seen that the peak water surface elevation (WSE, so called water level in the IPET report) computed by the present model is approximately 3.33 m at the IHNC-Lakefront Airport site. In addition, it is seen that an abrupt fall and rise of water level (3.17 m) within 2 hours is computed by the present model at the IHNC-Lakefront Airport site; in other words, this sudden change of water surface elevation (WSE) can caused a severe damage to the ships mooring around the entrance of the Inner Harbor Navigation Canal (IHNC). Furthermore, it is seen that the peak water surface elevation induced by the Route 3-travelingHurricane Katrina is slightly higher than the peak water surface level induced by the Route 1-traveling Hurricane Katrina at the IHNC-Lakefront Airport site (3.33 m versus 3.30 m) after comparing the computed hydrograph made under the wind generated by the Route 3-traveling Hurricane Katrina with the one made under the wind generated by the Route 1-traveling Hurricane Katrina (see the solid red line on Figure 4.103); however, the general trend of the fall and rise of water level induced by the wind generated by the Route 3-traveling Hurricane Katrina is entirely different from the general trend of the rise and fall of water level induced by the wind generated by the Route 1-traveling Hurricane Katrina. Therefore, it can be claimed that hurricane passing over Lake Pontchartrain with another route can cause evident differences in water surface elevation although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

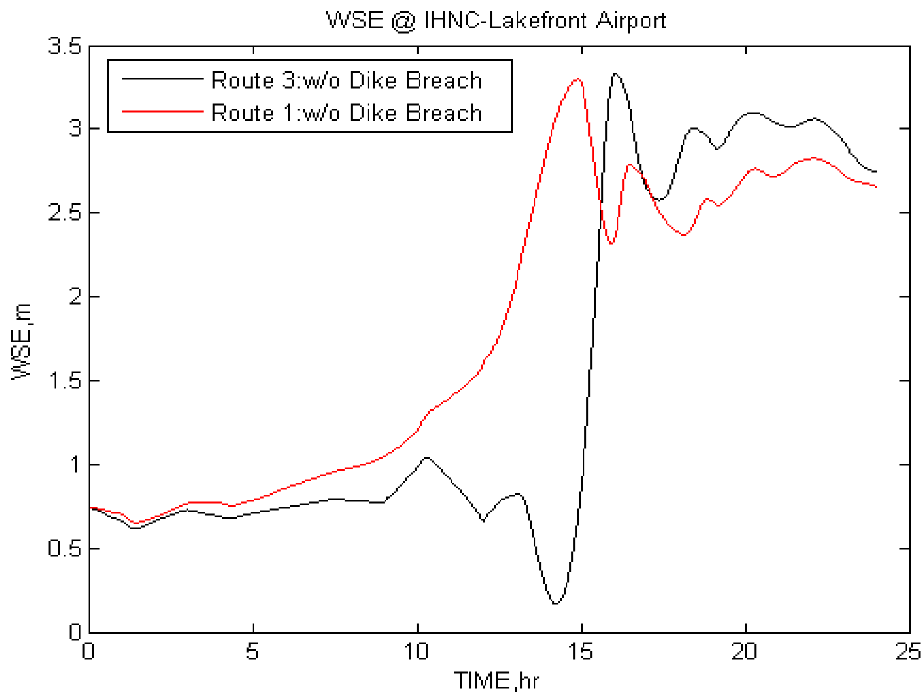

Figure 4.103 Computed Hydrograph, IHNC-Lakefront Airport

The computed hydrograph (solid black line) obtained from the present model for the Midlake is presented on Figure 4.104. From Figure 4.104, it is seen that the peak water surface elevation induced by the Route 3-traveling Hurricane Katrina is higher than the peak water surface level induced by the Route 1-traveling Hurricane Katrina at the Midlake site after comparing the computed hydrograph made under the wind generated by the Route 3-traveling Hurricane Katrina with the one made under the wind generated by the Route 1-traveling Hurricane Katrina (see the solid red line on Figure 4.104). Furthermore, the general trend of the rise and fall of water level induced by the wind generated by the Route 3-traveling Hurricane Katrina is evidently different from the general trend of the rise and fall of water level induced by the wind generated by the

Route 1-traveling Hurricane Katrina. Therefore, it can be claimed that these significant differences in the water surface elevations are caused by a hurricane passing over Lake Pontchartrain with another route although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

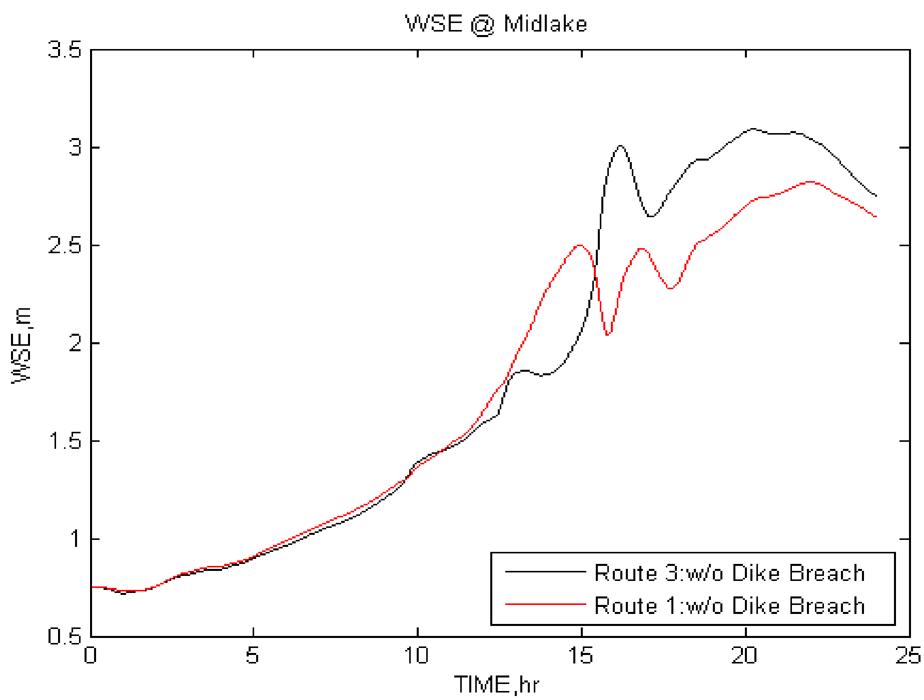

Figure 4.104 Computed Hydrograph, Midlake

The computed hydrograph (solid black line) obtained from the present model for Bayou La Branche (named Bayou Labranch in the IPET report) is presented on Figure 4.105. It can be seen from Figures 4.7 and 4.13 that Bayou La Branche is in the swamp along the southwest shore of Lake Pontchartrain and the swamps along the entire southwest shore of Lake Pontchatrain have been assigned into the computational domain for the current

numerical simulations performed by the FVM model. From Figure 4.105, it is seen that the peak water surface elevation induced by the Route 3-traveling Hurricane Katrina is much higher than the peak water surface level induced by the Route 1-traveling Hurricane Katrina at Bayou La Branche site after comparing the computed hydrograph made under the wind generated by the Route 3-traveling Hurricane Katrina with the one made under the wind generated by the Route 1-traveling Hurricane Katrina (see the solid red line on Figure 4.105). Besides, the general trends of the rise and fall of water levels on both computed hydrographs (solid black and solid red lines on Figure 4.105) made by the present model are almost identical although the highest water surface elevations induced by the winds generated by two hurricanes (Route 3-traveling Katrina and Route 1-travling Katrina) are slightly different at Bayou La Branche site. Therefore, it can be claimed that this evident difference in the water surface elevation is caused by a hurricane passing over Lake Pontchartrain with another route although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

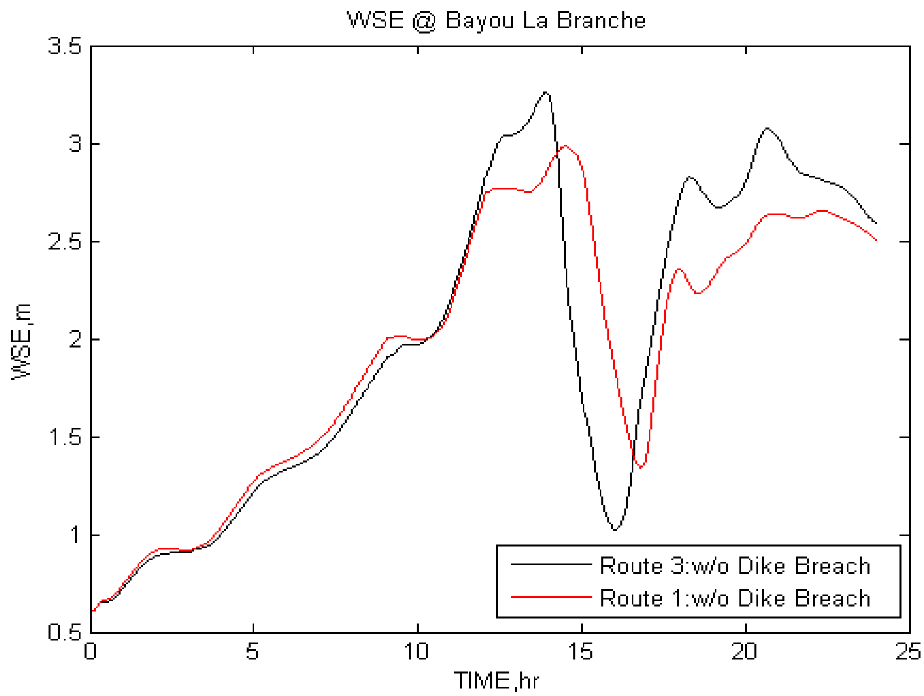

Figure 4.105 Computed Hydrograph, Bayou La Branche

The computed hydrograph (solid black line) obtained from the present model for Pass Manchac-Turtle Cove is presented on Figure 4.106. From Figures 4.7 and 4.13, it can be seen that Pass Manchac is a the narrow strip of water connecting Lake Pontchartrain and Lake Maurepas and the entire Pass Manchac is included in the computational domain used in the current numerical simulations performed by the present model. From Figure 4.106, it is seen that the peak water surface elevation induced by the Route 3-traveling Hurricane Katrina is much higher than the peak water surface level induced by the original Hurricane Katrina at Pass Manchac-Turtle Cove site after comparing the computed hydrograph made under the wind generated by the Route 3-traveling Hurricane Katrina with the one made under the wind generated by the Route 1-traveling Hurricane

Katrina (see the solid red line on Figure 4.106). Besides, the general trend of the rise and fall of water level induced by the wind generated by the Route 3-traveling Hurricane Katrina is entirely different from the general trend of the rise and fall of water level induced by the wind generated by the Route 1-traveling Hurricane Katrina. Therefore, it can be claimed that this significant difference in the water surface elevation is caused by a hurricane passing over Lake Pontchartrain with another route although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

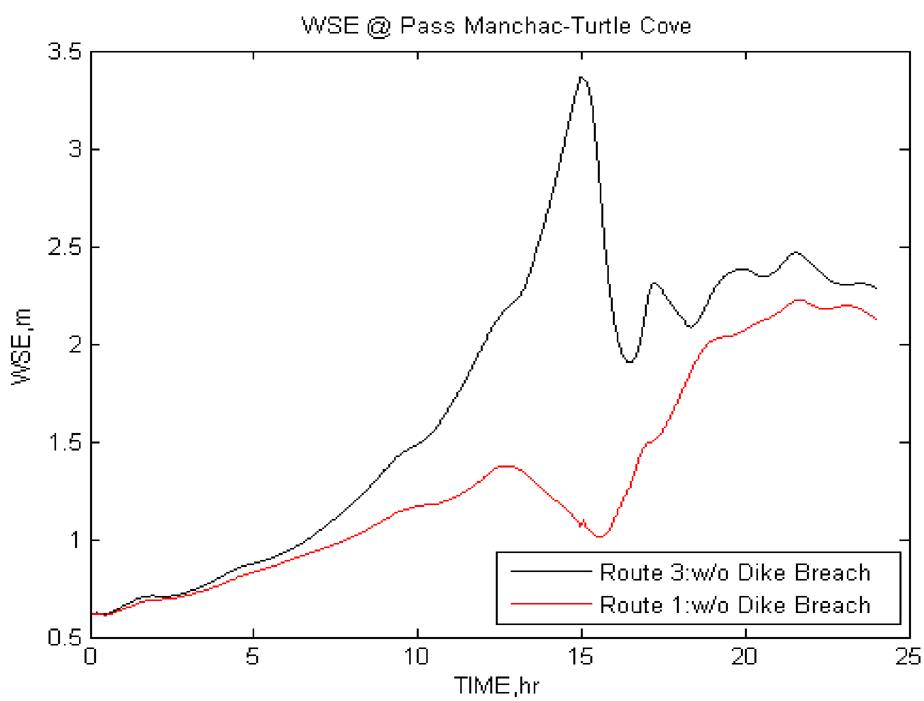

Figure 4.106 Computed Hydrograph, Pass Manchac-Turtle Cove

The computed hydrograph (solid black line) obtained from the present model for Little Irish Bayou is presented on Figure 4.107. From Figure 4.107, it is seen that the peak water surface elevation induced by the Route 3-traveling Hurricane Katrina is much higher than the peak water surface level induced by the Route 1-traveling Hurricane Katrina at Little Irish Bayou site after comparing the computed hydrograph made under the wind generated by the Route 3-traveling Hurricane Katrina with the one made under the wind generated by the Route 1-traveling Hurricane Katrina (see the solid red line on Figure 4.107). Besides, the general trends of the rise and fall of water levels on both computed hydrographs (solid black and solid red lines on Figure 4.107) made by the present model are almost identical although the highest water surface elevations induced by the winds generated by two hurricanes (Route 3-traveling Katrina and Route 1-travling Katrina) are slightly different at Little Irish Bayou site. Therefore, it can be claimed that this evident difference in the water surface elevation is caused by a hurricane passing over Lake Pontchartrain with another route although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

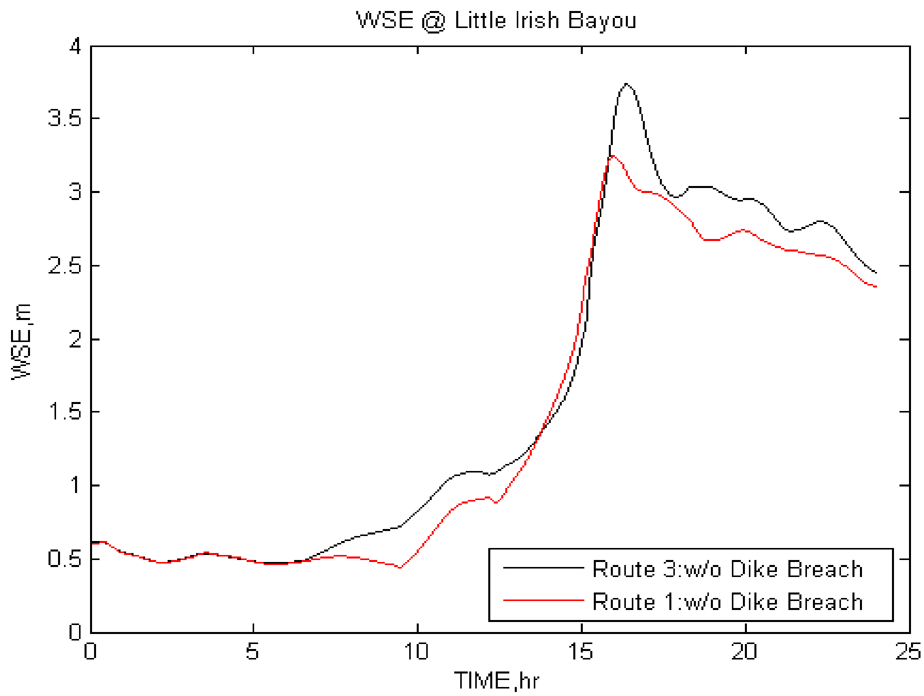

Figure 4.107 Computed Hydrograph, Little Irish Bayou

The computed hydrographs of the water surface elevation (WSE) showing on S-N and W-E cross-sections of Lake Pontchartrain induced by the wind generated through the Route 3 –Traveling Hurricane Katrina (see Figure 4.28) are presented on Figures 4.108 and 4.109, respectively. It is seen from Figures 4.108 and 4.109 that the wind-induced oscillations in Lake Pontchartrain are the evident phenomena as Hurricane Katrina progressed over the west shore and its surrounding regions of Lake Pontchartrain (Route 3 shown in Figure 4.28). In the following paragraphs, the hourly contour maps of the water surface elevation (WSE) for the entire Lake Pontchartrain, as Hurricane Katrina progressed over the west shore and its surrounding regions of Lake Pontchartrain (Route

3 shown in Figure 4.28), are used to investigate the oscillations of semi-enclosed water body induced by hurricanes under specific routes.

The hourly contour maps of the computed water surface elevation (WSE) for the entire Lake Pontchartrain induced by the wind generated through the Route 3-traveling Hurricane Katrina are presented from Figures 4.110 to Figures 4.134. The time-frame of these contour maps is from 12:00 am UTC August 29, 2005 to 12:00 am UTC August 30, 2005. It is assigned that $t = 0$ is at 11:59:15 pm UTC August 28, 2005 and consequently the reference WSE at $t = 0$ is zero. Therefore, the oscillation phenomenon is not evident throughout entire Lake Pontchartrain at the starting moment of the numerical simulation (12:00 am August 29, 2005), as it is seen from Figure 4.110. As it is seen from Figures 4.2 and 4.28, the original Hurricane Katrina did not make its landfall until 6:10 am CDT (11:10 am UTC) August 29 at Southeast Louisiana and the distance between the Route 1 and Route 3 is approximately 72 km; besides, the oscillation induced by tides from Gulf of Mexico into Lake Pontchartrain is not influential in this study, this is a reasonable assumption that the oscillations in Lake Pontchartrain induced by wind generated by the Route 3-traveling Hurricane Katrina can be focused on the 24-hours period between 12:00 am UTC August 29, 2005 and 12:00 am UTC August 30, 2005.

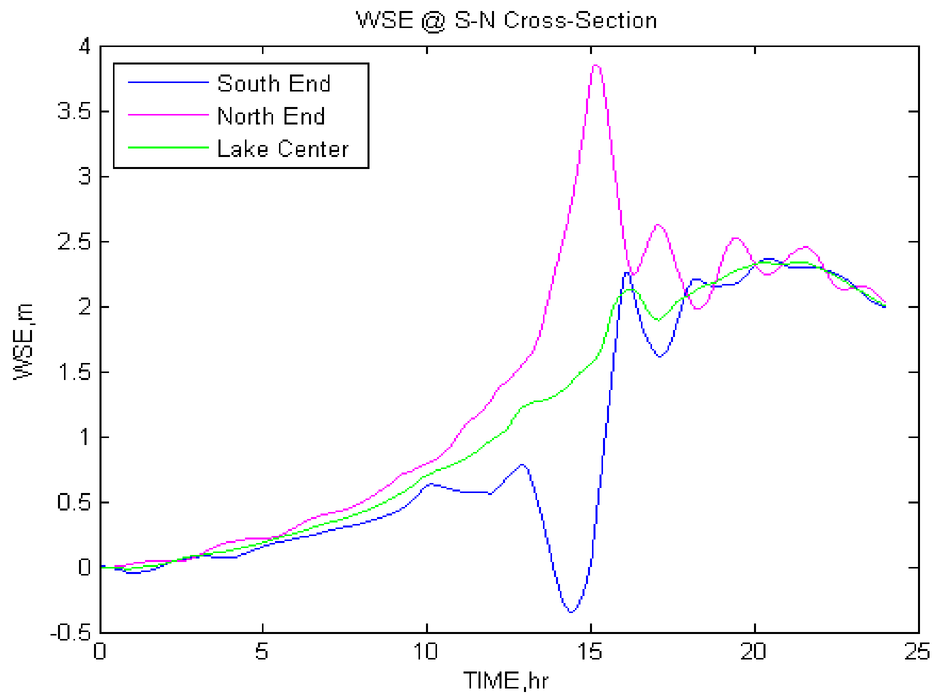

Figure 4.108 Hydrographs of the S-N cross-section

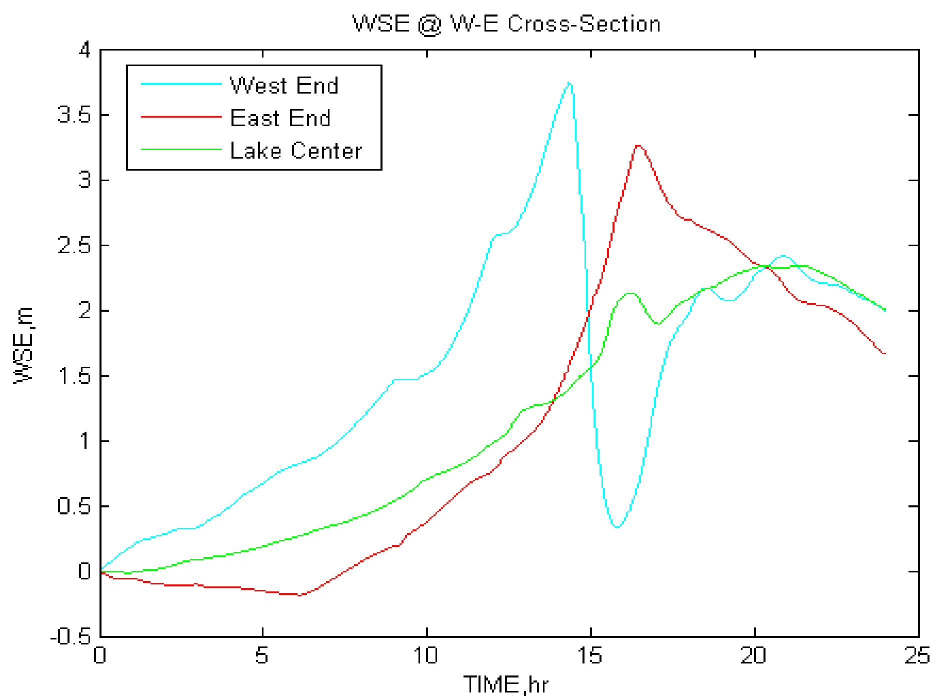

Figure 4.109 Hydrographs of the W-E cross-section

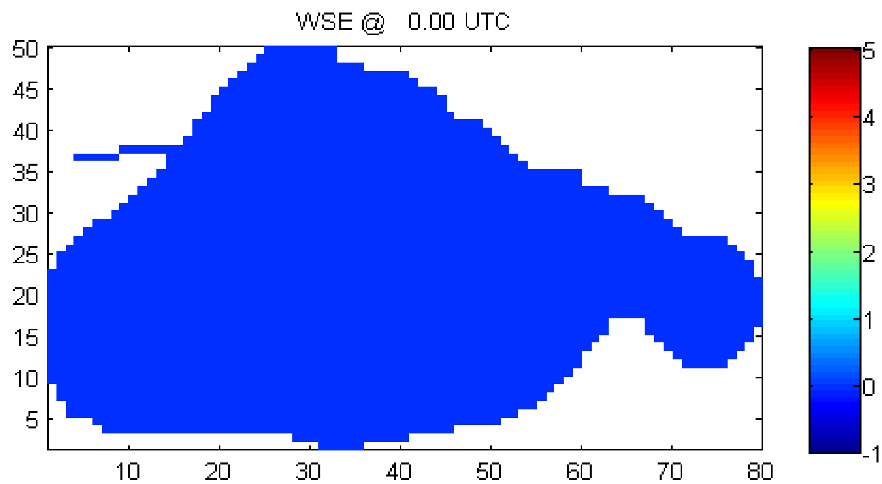

Figure 4.110 Contours of WSE at 12:00 am (UTC) August 29, 2005

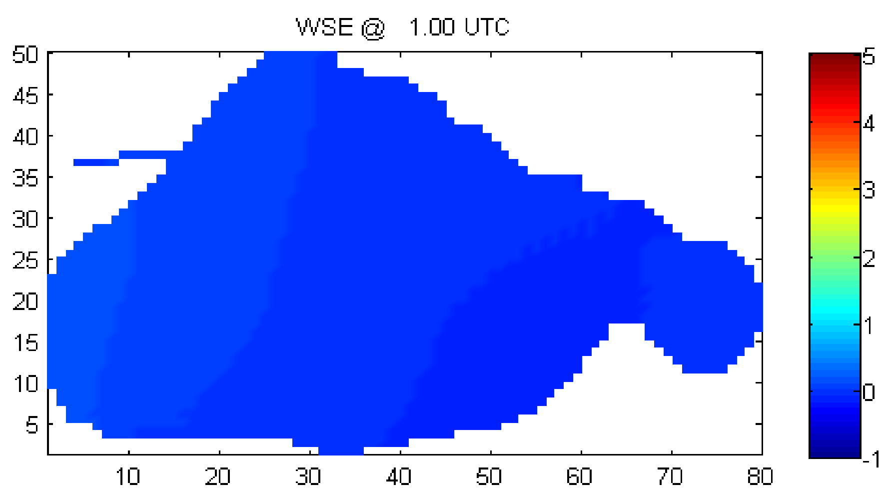

Figure 4.111 Contours of WSE at 01:00 am (UTC) August 29, 2005

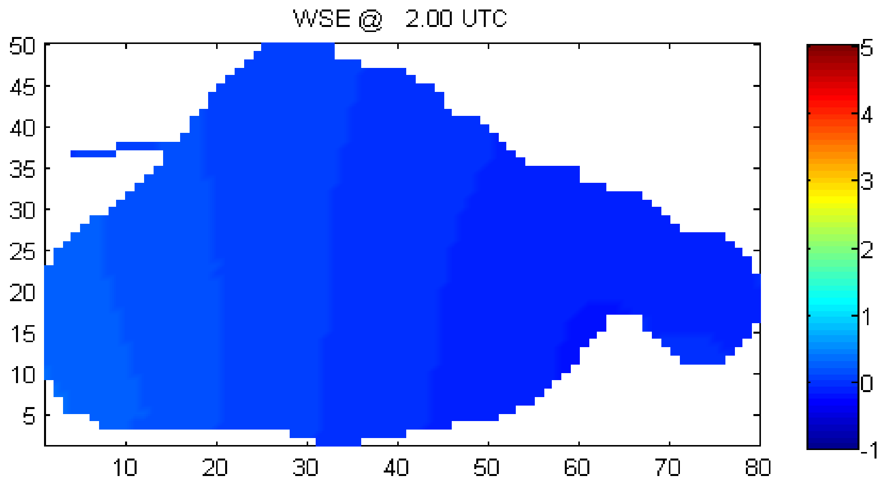

Figure 4.112 Contours of WSE at 02:00 am (UTC) August 29, 2005

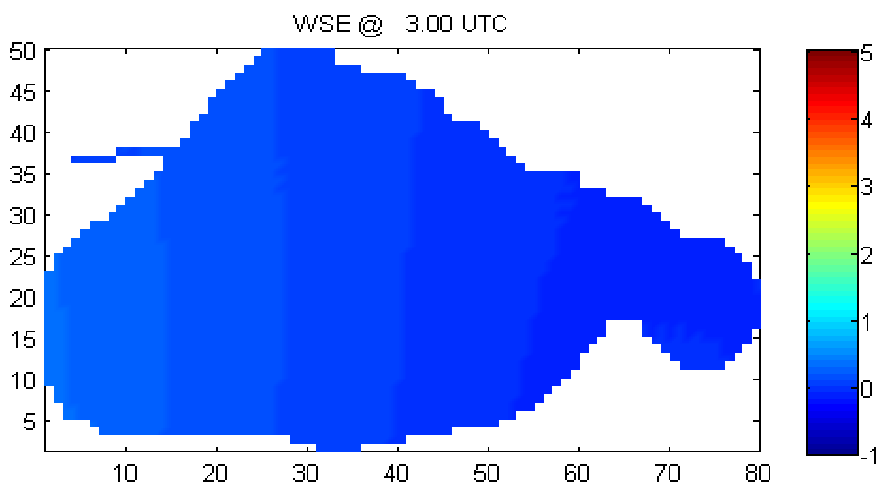

Figure 4.113 Contours of WSE at 03:00 am (UTC) August 29, 2005

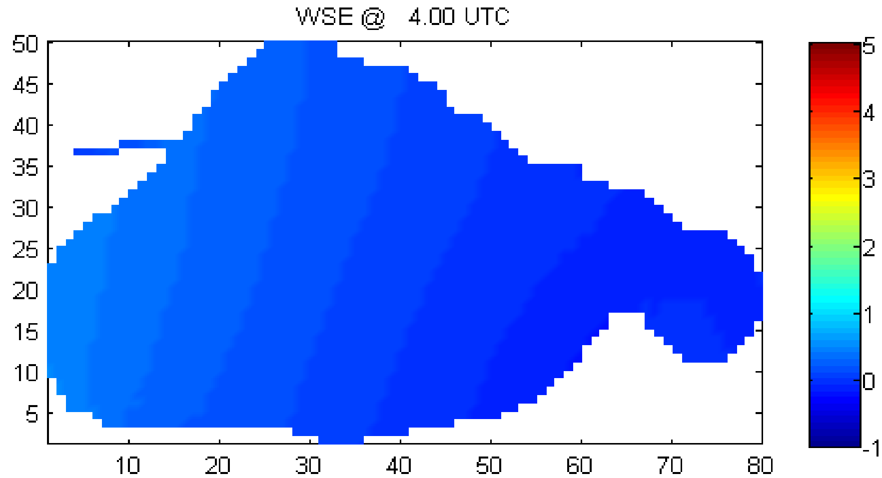

Figure 4.114 Contours of WSE at 04:00 am (UTC) August 29, 2005

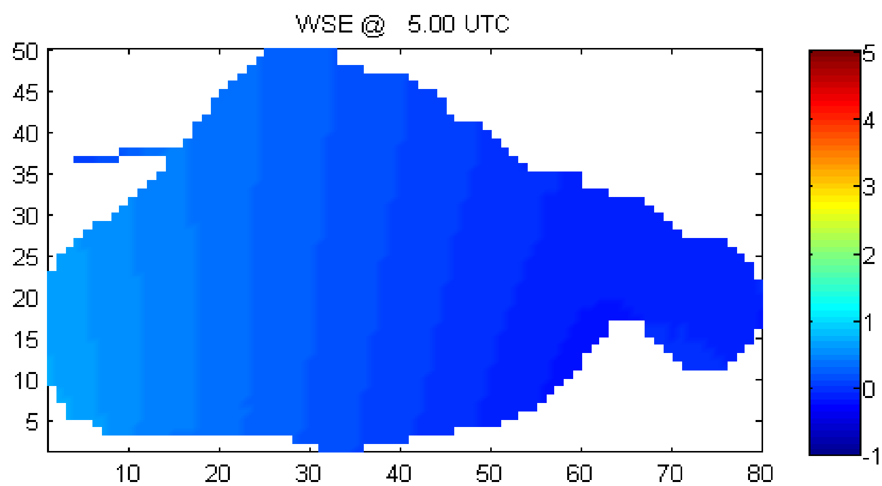

Figure 4.115 Contours of WSE at 05:00 am (UTC) August 29, 2005

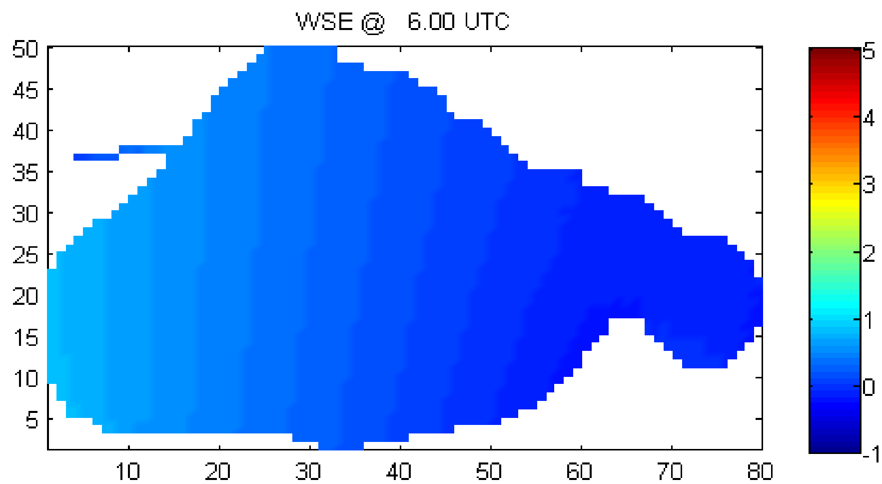

Figure 4.116 Contours of WSE at 06:00 am (UTC) August 29, 2005

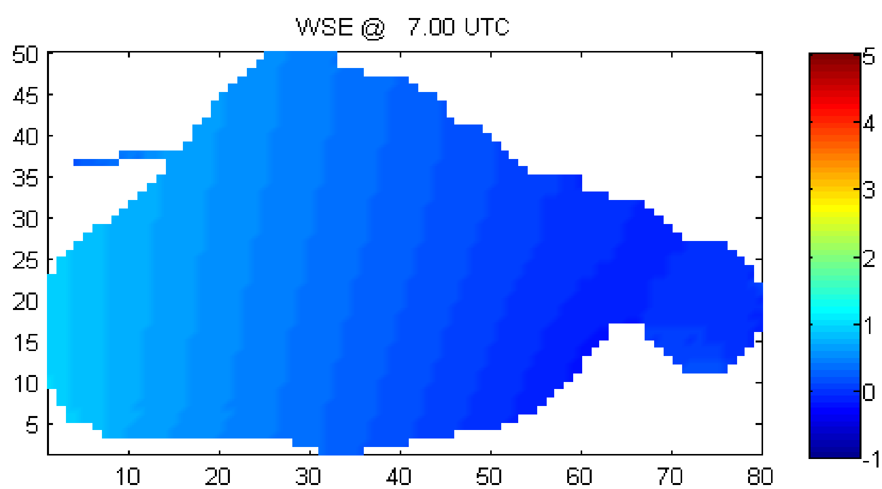

Figure 4.117 Contours of WSE at 07:00 am (UTC) August 29, 2005

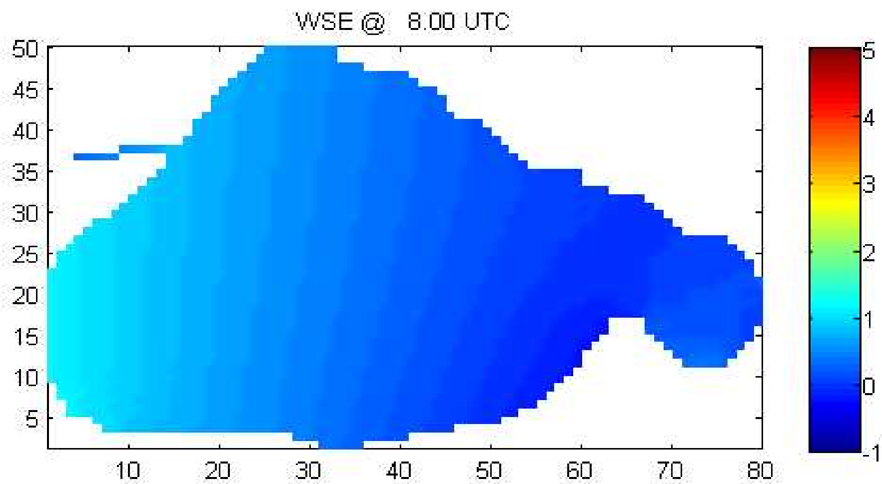

Figure 4.118 Contours of WSE at 08:00 am (UTC) August 29, 2005

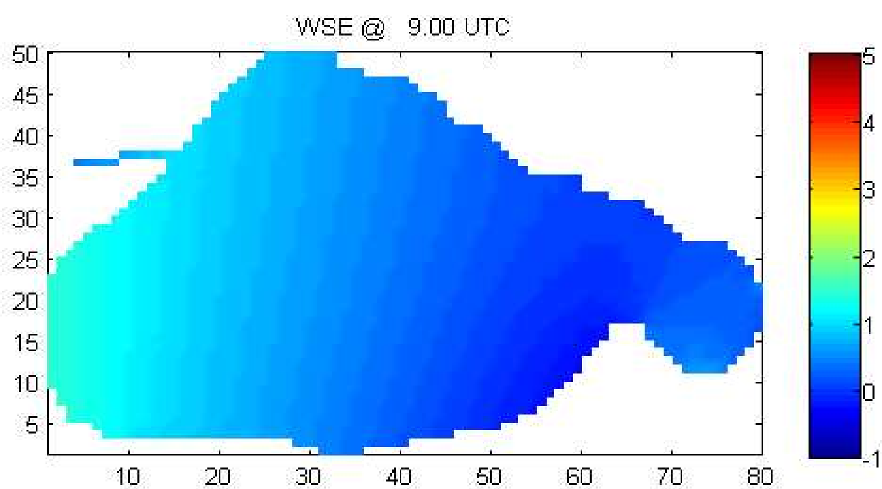

Figure 4.119 Contours of WSE at 09:00 am (UTC) August 29, 2005

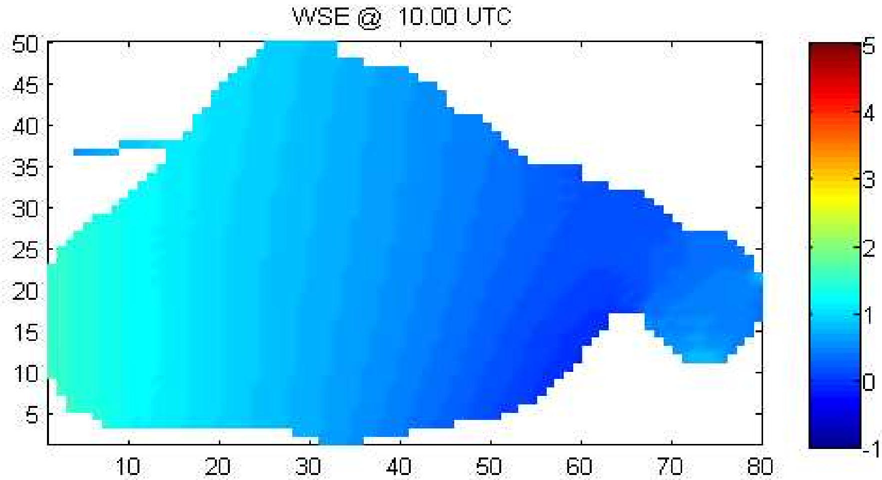

Figure 4.120 Contours of WSE at 10:00 am (UTC) August 29, 2005

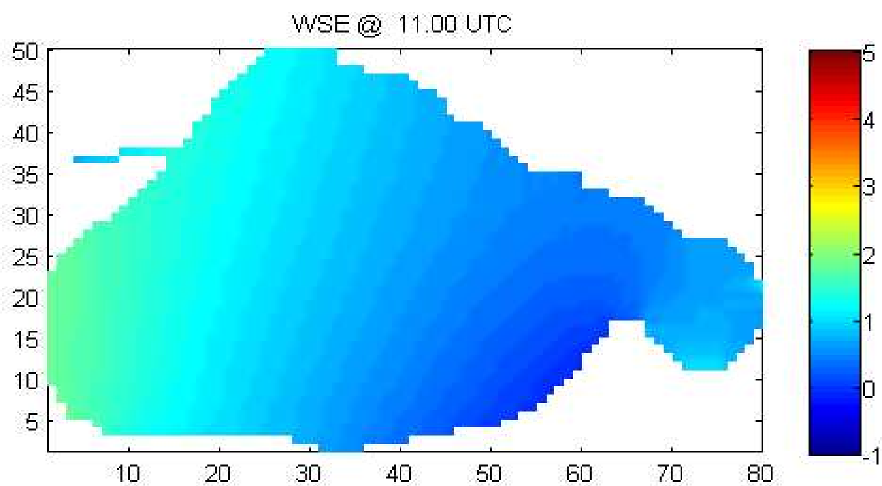

Figure 4.121 Contours of WSE at 11:00 am (UTC) August 29, 2005

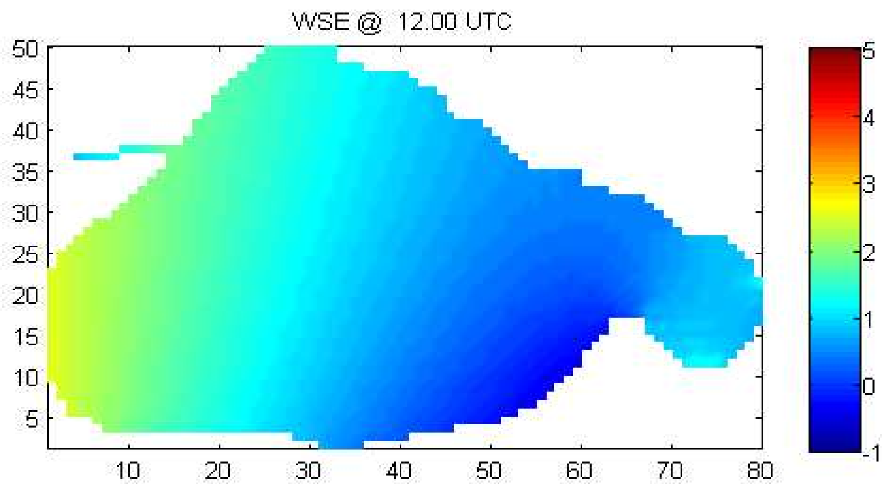

Figure 4.122 Contours of WSE at 12:00 pm (UTC) August 29, 2005

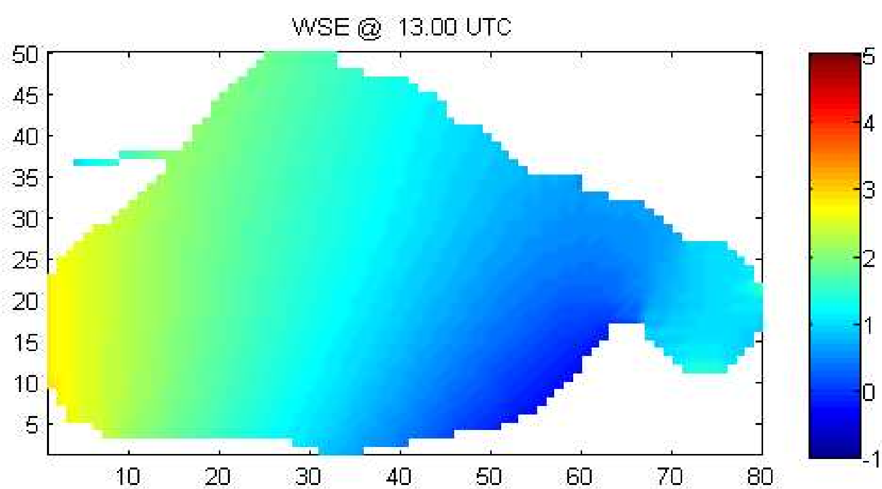

Figure 4.123 Contours of WSE at 01:00 pm (UTC) August 29, 2005

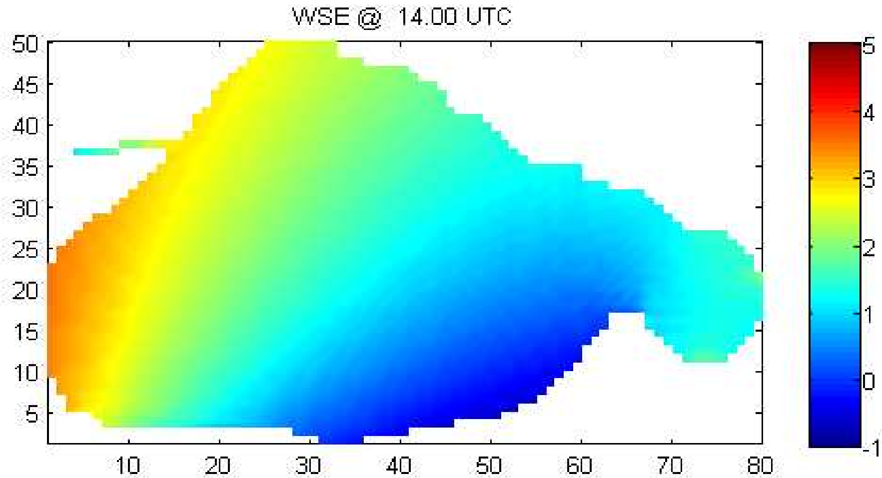

Figure 4.124 Contours of WSE at 02:00 pm (UTC) August 29, 2005

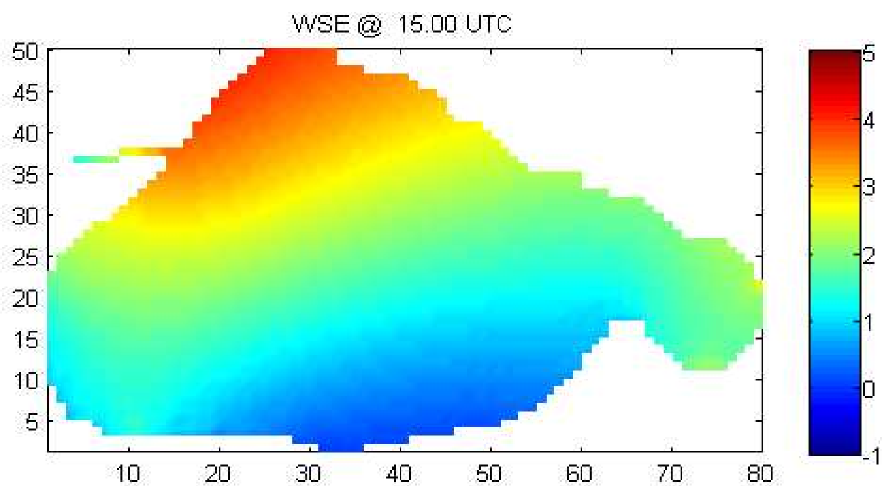

Figure 4.125 Contours of WSE at 03:00 pm (UTC) August 29, 2005

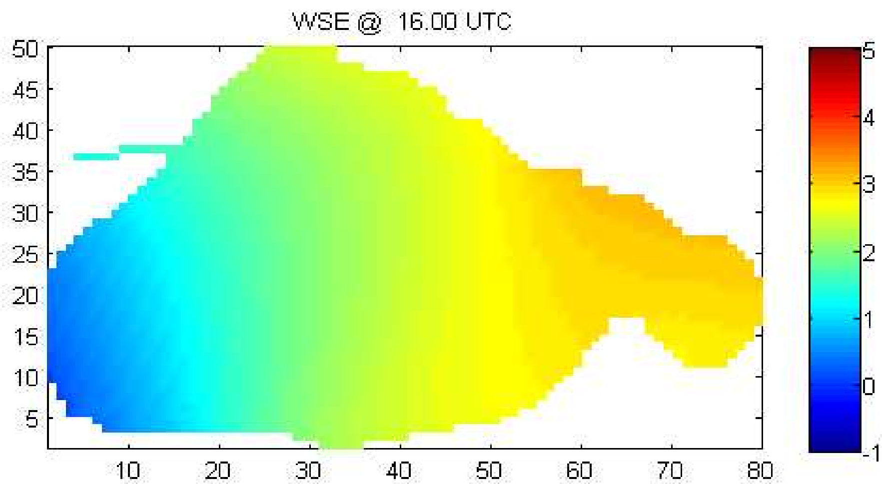

Figure 4.126 Contours of WSE at 04:00 pm (UTC) August 29, 2005

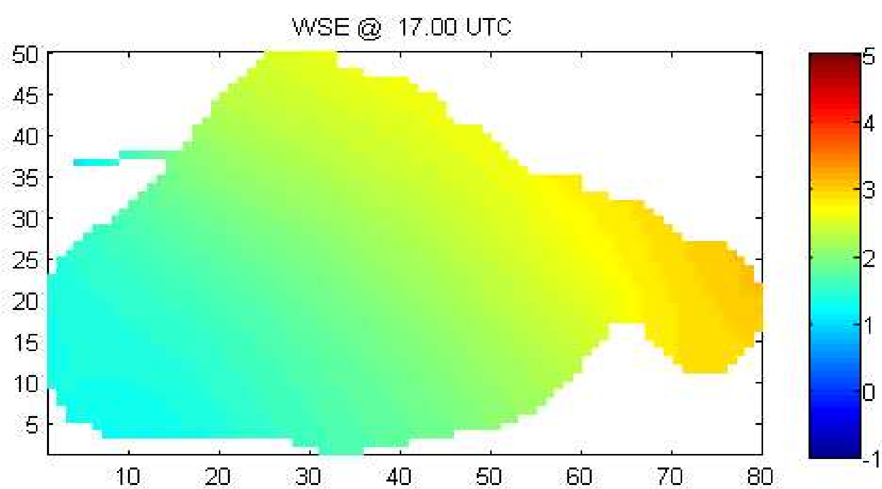

Figure 4.127 Contours of WSE at 05:00 pm (UTC) August 29, 2005

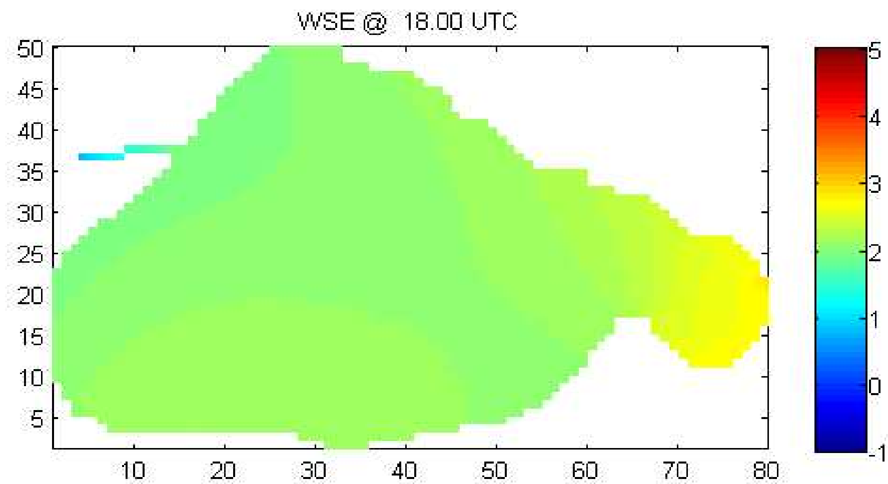

Figure 4.128 Contours of WSE at 06:00 pm (UTC) August 29, 2005

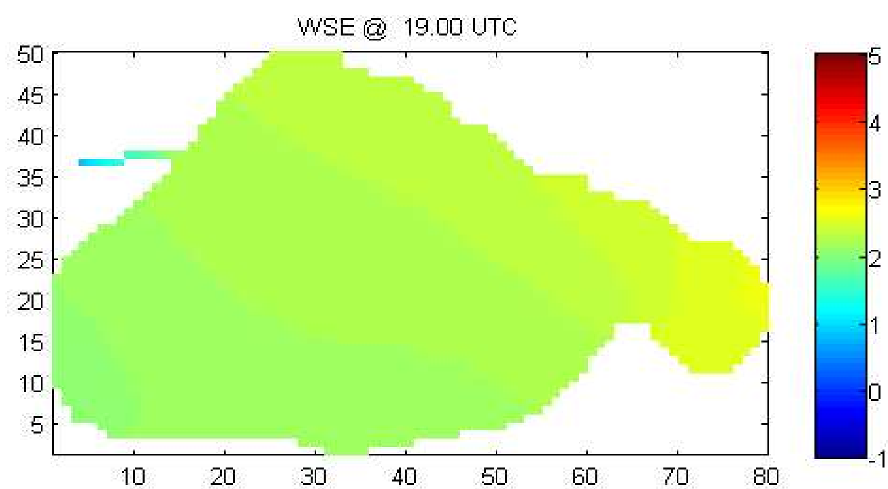

Figure 4.129 Contours of WSE at 07:00 pm (UTC) August 29, 2005

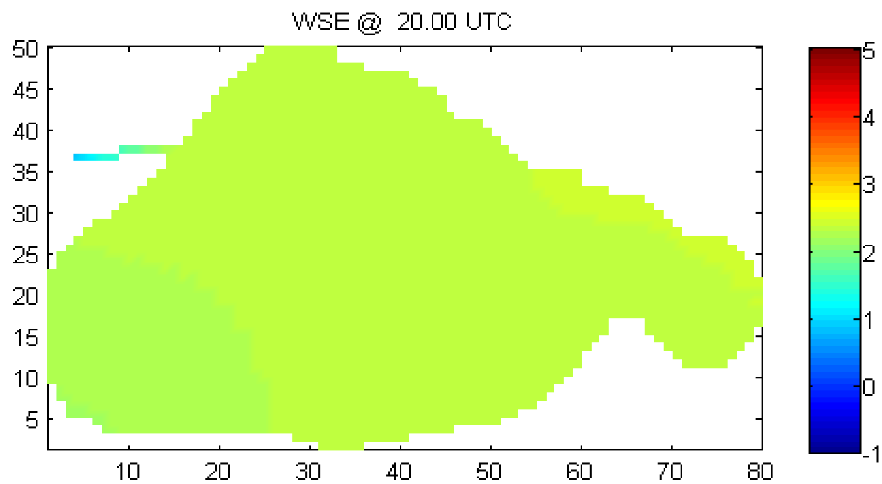

Figure 4.130 Contours of WSE at 08:00 pm (UTC) August 29, 2005

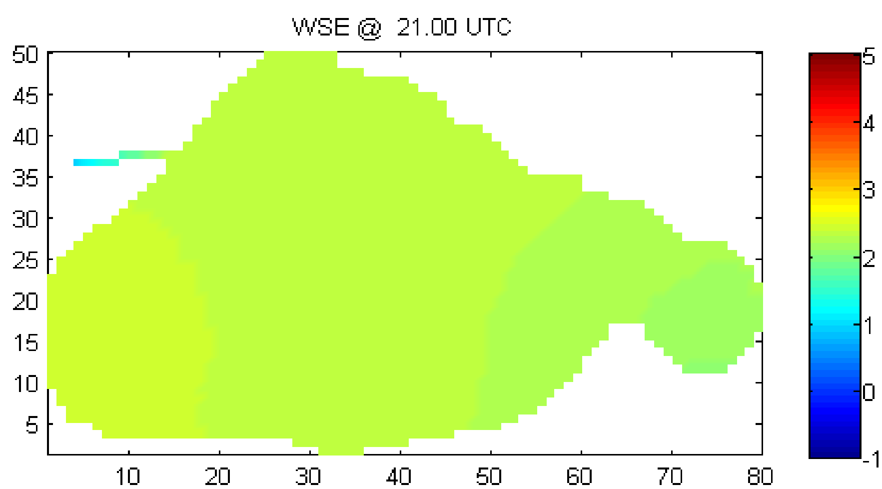

Figure 4.131 Contours of WSE at 09:00 pm (UTC) August 29, 2005

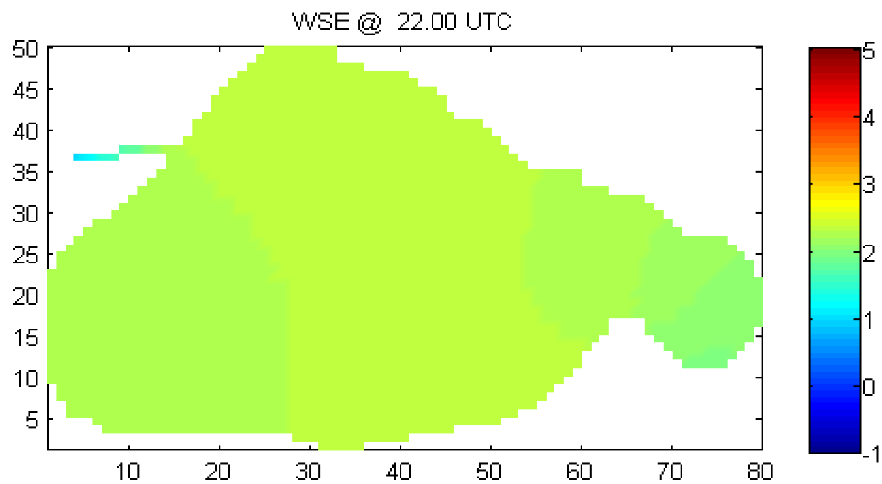

Figure 4.132 Contours of WSE at 10:00 pm (UTC) August 29, 2005

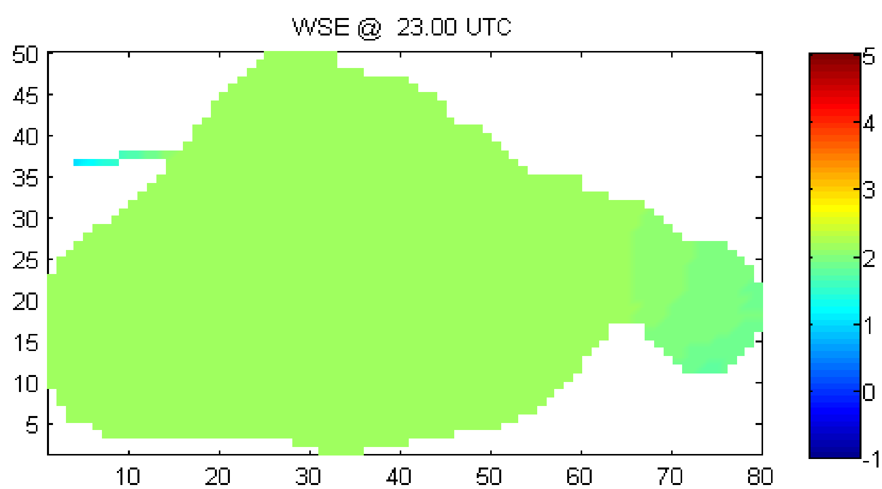

Figure 4.133 Contours of WSE at 11:00 pm (UTC) August 29, 2005

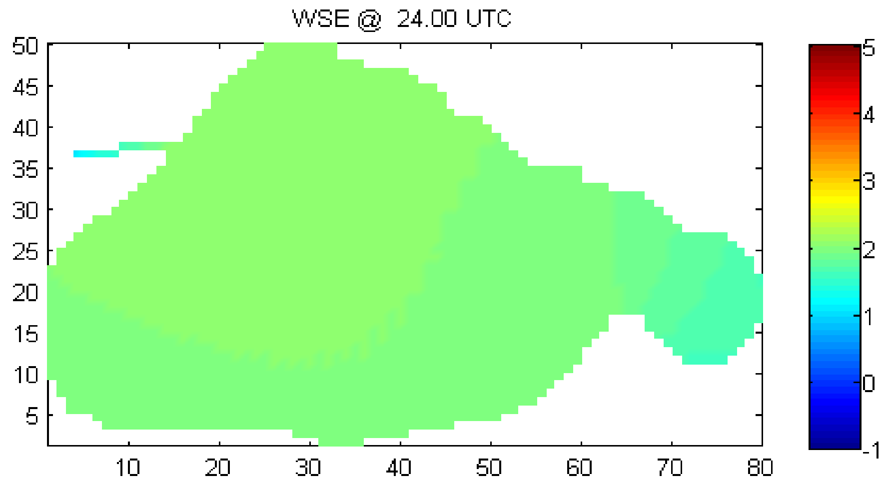

Figure 4.134 Contours of WSE at 12:00 am (UTC) August 30, 2005

It can be seen from Figures 4.111 to 4.113 that the oscillation in Lake Pontchartrain is built up as Hurricane Katrina approaches to Southeast Louisiana and it becomes more obvious as time goes by. It is very evident that the direction of node line ($\eta = 0$) in the lake is in the North-South orientation. It is seen that the water in the east part of the lake is driven by the wind to the west part of the lake during the first 3-hour period, as we examine the temporal variations of the contours of WSE from 12:00 to 03:00 am UTC August 29, 2005. The strength of Hurricane Katrina, according to the IPET report, remains Category 4 in Saffir-Simpson Scale within this 3-hours period.

It is possible that the Route 3-traveling Hurricane Katrina makes its landfall at Southeast Louisiana around 11:00 am UTC (6:00 am Local Time) August 29 since the distance between Route 1 and Route 3 is about only 72 km (see Figures 4.2 and 4.28). As the Route 3-traveling Hurricane Katrina approaches Southeast Louisiana, the magnitude of oscillation in Lake Pontchartrain gradually increases between 04:00 am UTC and 09:00 am UTC August 29, 2005. During this 6-hours period, the direction of node line ($\eta = 0$) in the lake slowly changes from the North-South orientation to the Northeast-Southwest orientation since the direction of the dominant wind alters as Hurricane Katrina approaches to Lake Pontchartrain; meanwhile, the strength of Hurricane Katrina, according to the IPET report, is gradually reducing from Category 4 to 3 in Saffir-Simpson Scale within this 6-hours period.. We can see these phenomena after examining the temporal variations of the contours of WSE from Figures 4.114 to 4.119.

As the Route 3-traveling Hurricane Katrina approaches Southeast Louisiana, the magnitude of oscillation in Lake Pontchartrain gradually increases between 09:00 am UTC and 12:00 pm UTC August 29, 2005. During this 3-hours period, the direction of node line ($\eta = 0$) in the lake remains the Northeast-Southwest orientation although the direction of the dominant wind alters as Hurricane Katrina approaches to Lake Pontchartrain while its strength remains Category 3. We can see these phenomena after examining the temporal variations of the contours of WSE from Figures 4.120 to 4.122.

From 12:00 pm UTC to 03:00 pm UTC August 29, the Route 3-traveling Hurricane Katrina passes over the west shore and its surrounding regions of Lake Pontchartrain. Thus, this close-encounter between the hurricane and the lake causes significant oscillations in Lake Pontchartrain as we compare the oscillations happened in the lake during the previous 12 hours. It is seen from Figures 4.123 to 4.125 that the direction of node line ($\eta = 0$) in the lake changes from the Northeast-Southwest orientation to the nearly East-West orientation as the direction of the dominant wind rapidly alters during this 3-hours period. Meanwhile, the magnitude of oscillation (the height of WSE) becomes higher than the previous 3 hours, and the oscillation along the northwest and north shores of Lake Pontchartrain reaches the highest magnitude between 02:30 and 03:00 pm UTC (or 09:30 and 10:00 am Local Time), as it is seen from the computed hydrograph for Pass Manchac (Figure 4.106). Within this 3-hours period, the strength of the Route 3-traveling Hurricane Katrina still remains Category 3.

During the next 3-hours period (from 03:00 to 06:00 pm UTC August 29), the Route 3-traveling Hurricane Katrina continuously crosses over the west shore and its surrounding regions of Lake Pontchartrain and moves inland with a nearly north direction while its strength reduces from Category 3 to 2; in other words, the wind generated by the hurricane gets weaker during this 3-hours time-period. Meanwhile, the direction of node line ($\eta = 0$) rapidly turns from the nearly East-West orientation in a clockwise pattern to the nearly North-South orientation even though the direction of the dominant wind alters

90° in a counterclockwise pattern. Because the surge propagates into Lake Pontchartrain from the Gulf of Mexico via Lake Borgne (see Figure 4.3), a huge amount of water flows into Lake Pontchartrain and the magnitude of oscillation (the height of WSE) in Lake Pontchartrain evidently increases even though the hurricane leaves the northwest regions of the lake. Furthermore, the node line ($\eta = 0$) disappears and the WSE in the entire lake is greater than the reference WSE ($\eta = 0$) from 05:00 pm, as it is seen from Figure 4.127. We can find these evidences from a thorough study of the temporal variations of the contours of WSE from Figures 4.126 to 4.128.

In the final 6-hours period (from 07:00 pm UTC August 29 to 12:00 am UTC August 30, 2005), the strength of the Route 3-traveling Hurricane Katrina continuously reduces from Category 2 to 1; furthermore, the Route 3-traveling Hurricane Katrina becomes a tropical storm as it moves inwardly into the northeastern region of the United States of America as the original Hurricane Katrina moves inwardly (see Figures 4.2 and 4.28). Although the direction of dominant wind keeps turning counterclockwise during this 6-hours period, the wind generated by the hurricane is drastically weaker than it was in the previous 18-hours period. Since the hurricane moves far away from the lake, the magnitude of oscillation in Lake Pontchartrain gradually reduces and is smaller than it was in the previous 6-hour period. Besides, the major sloshing motion is moving toward the east within this 6-hours period. The WSE in the lake does not significantly recede since there is not enough wind stress to drive out the water from Lake Pontchartrain to

Lake Borgne and other surrounding water bodies (for example, Lake Maurepas); hence, the WSE in the entire lake is greater than the reference WSE ($\eta = 0$) in this 6-hours period. Meanwhile, there is a significant drawdown in the east portion of Lake Pontchartrain at the finale of the numerical simulation (09:00 pm August 29 to 12:00 am August 30, 2005) as it is seen from Figures 4.131 to 4.134. We can obtain these discoveries by examining the temporal variations of WSE from Figures 4.129 to 4.134. Furthermore, the significant findings drawn from these hourly contour maps (from Figures 4.110 to 4.134) are summarized in the following paragraphs.

The Route 3-traveling Hurricane Katrina moves in a nearly north direction and passes over the west shore and its surrounding regions of Lake Pontchartrain between 12:00 am and 06:00 pm UTC August 29, 2005 corresponding to the first 18-hours of the numerical simulations made by the present model. The closest encounter between Hurricane Katrina and Lake Pontchartrain takes place between 12:00 and 06:00 pm UTC (or 7:00 am and 1:00 pm Local Time) August 29, 2005 (see Figure 4.2). During this 6-hours period, there are three significant factors of Hurricane Katrina needed to be reviewed:

1. The hurricane remains Category 3 intensity of Saffir-Simpson Scale until 03:00 pm UTC (10:00 am Local Time), after which the strength of the hurricane gradually reduces to Category 2.
2. The hurricane is moving in a nearly north direction with an approximate speed of 27 to 29 km/hr.
3. The eye of the Route 3-traveling Hurricane Katrina passes through the west shore of Lake Pontchartrain.

Because of these three unique characteristics of the interaction between the hurricane and the lake, the sloshing motion of the lake water surface changes in a clockwise pattern in the lake; however, the hurricane itself rotates in the counterclockwise character. In detail, the dominant sloshing motion at Lake Pontchartrain turns from the northwest to the east within this 6-hours period. During this 6-hours, the lowest amplitude of oscillation (minimum WSE) along the south shore of the lake happens between 02:30 and 03:00 pm UTC (between 09:30 and 10:00 am Local Time); on the contrary, the highest measured water level along the south shore of Lake Pontchartrain during the invasion of the original Hurricane Katrina (Route 1-traveling Hurricane Katrina) happens during this 6-hours period (Route 1 shown in Figure 4.28). Meanwhile, the highest amplitude of oscillation (maximum WSE) along the south shore of the lake happens between 03:00 and 03:30 pm UTC (between 10:00 and 10:30 am Local Time) with a magnitude of 3.11 m to 3.33 m predicted by the present model.

Furthermore, the moving direction of the storm surge changes from the west direction to the east direction within the first 16-hours period (12:00 am to 04:00 pm UTC August 29, 2005) of the numerical simulations (see Figures 4.110 to 126); in other words, the sloshing motion changes 180° in 16 hours. Besides, the oscillation (rise and fall of water level) in a semi-enclosed lake induced by a hurricane can be moving around the lake in a clockwise-turning pattern although the direction of dominant wind generated by the hurricane alters in a counterclockwise pattern. In detail, the moving direction of the oscillation of a semi-enclosed water body induced by a hurricane rotates in a clockwise pattern even though a hurricane circulates counterclockwise and the direction of the accompanying wind generated by the hurricane can turn in a counterclockwise pattern. Meanwhile, the magnitude of oscillation thoroughly depends on the strength (wind speed) and the duration (length in time) of the wind to a specific direction; in detail, the magnitude of the oscillation (height of rise and fall) associated with the moving direction will be different at each specific location around the lake.

4.5.4 Hurricane Katrina Traveling With Reduced Forward Speeds

The present model is used to study the oscillation in Lake Pontchartrain induced by wind generated by the Route 1-traveling Hurricane Katrina with reduced forward speeds (see Figure 4.28). The dimensions of the uniform rectangular control-volumes (CV's) in a Cartesian grid are $(\Delta x, \Delta y) = (750\,m, 750\,m)$. The time-step Δt is chosen to be 45 seconds. The bathymetry of Lake Pontchartrain adopted from the Interagency Performance Evaluation Task Force (IPET) report is used in the numerical simulations (see Figure 4.14). The time-period in the numerical simulations for the oscillation in Lake Pontchartrain induced by wind generated by the Route 1-traveling Hurricane Katrina with reduced forward speeds is from 12:00 am UTC (Coordinated Universal Time) August 29, 2005 to 12:00 am UTC August 30, 2005, or 07:00 pm CDT (Central Daylight Time) August 28, 2005 to 07:00 pm CDT August 29, 2005. During this 24-hours time-period, Hurricane Katrina will make two landfalls at Southeast Louisiana and will pass through the region along the east shore of Lake Pontchartrain (see Figures 4.2 and 4.28). Hence, the study of the oscillation in Lake Pontchartrain induced by wind generated by the Route 1-traveling Hurricane Katrina with reduced forward speeds can be concentrated in this 24-hours period. In order to study the oscillation phenomena in Lake Pontchartrain induced by the Route-1 traveling Hurricane Katrina with reduced forward speeds, the breaches and/or overtopping of floodwalls and levees along Lake Pontchartrain will not be accommodated into the numerical simulations performed by the present model for this case; hence, the water can not flow out of the lake through the entrances of the canals connecting to the lake during the entire 24-hours period of the numerical simulations for the oscillations of Lake Pontchartrain induced by the Route-1 traveling Hurricane Katrina with reduced forward speeds.

The wind field inducing the oscillations in Lake Pontchartrain is exclusively caused by the Route 1-traveling Hurricane Katrina with reduced forward speeds. The numerical typhoon (or hurricane) model, based on Equation (3.9) through Equation (3.14) in Chapter 3 and developed along with the present model in this study, is used to generate the pressure and wind fields. The necessary meteorological data to simulate Hurricane Katrina between 12:00 am UTC August 29, 2005 and 12:00 am UTC August 30, 2005 are adopted and modified from the Interagency Performance Evaluation Task Force (IPET) report and are listed in Table 4.2. The diameters of the eye of the simulated Hurricane Katrina by the numerical hurricane model are the distances corresponding to a time interval of a half-hour traveling of the simulated Hurricane Katrina. The forward speeds for the simulated Hurricane Katrina derived from the moving path of the original Hurricane Katrina between 12:00 am UTC August 29, 2005 and 12:00 am UTC August 30, 2005 are interpreted and adjusted from the hourly Latitudes and Longitudes of Hurricane Katrina recorded in the Interagency Performance Evaluation Task Force (IPET) report for the numerical simulation.

Table 4.2 Characteristics of a Hurricane Required in the Numerical Simulation

Date/Time (UTC)	**Central Pressure (bar)**	**Radius to Maximum Winds (m)**
Aug 29 0000	90400	34000
Aug 29 0300	90600	34000
Aug 29 0600	90800	34000
Aug 29 0900	91000	34000
Aug 29 1200	91350	47000
Aug 29 1500	91700	58000
Aug 29 1800	92300	67000
Aug 29 2100	93200	37000
Aug 30 0000	94800	42000

The computed hydrograph (solid black line) obtained from the present model for the 17th Street Canal is presented on Figure 4.135. From Figure 4.135, it is seen that the peak water surface elevation (WSE, so called water level in the IPET report) computed by the present model is approximately 4.45 m at the 17th Street Canal site. Besides, it is seen that the peak water surface elevation induced by the Route 1-traveling Hurricane Katrina with reduced forward speeds is much larger than the peak water surface level induced by the Route 1-traveling Hurricane Katrina at the 17th Street Canal site (4.45 m versus 3.30 m) after comparing the computed hydrograph made under the wind generated by the hurricane with the one made under the wind generated by the Route 1-traveling

Hurricane Katrina (see the solid red line on Figure 4.135). Therefore, it can be claimed that this significant difference in water surface elevation is caused by a hurricane passing over Lake Pontchartrain with different forward speeds although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

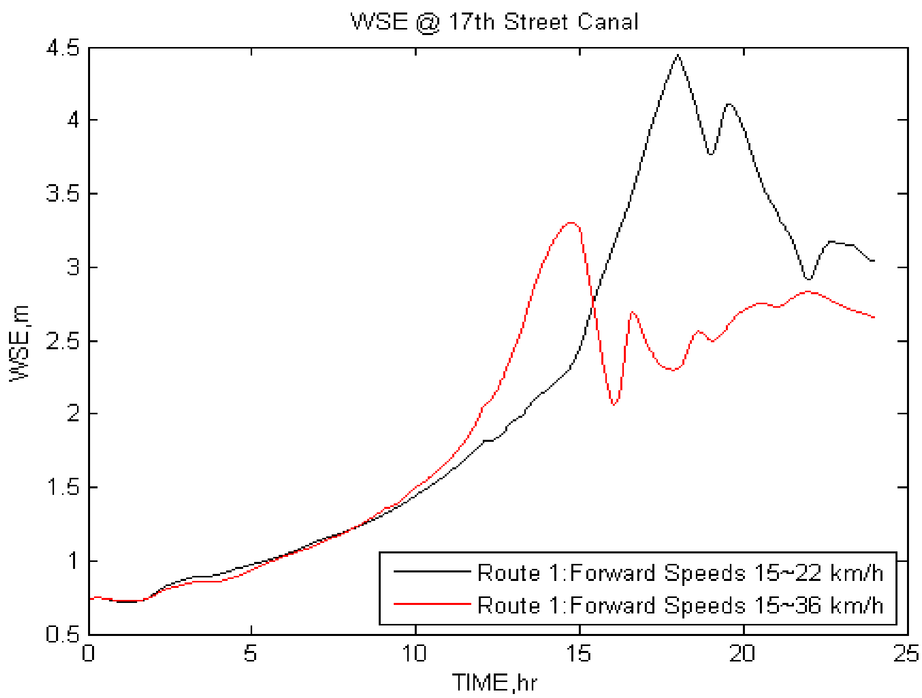

Figure 4.135 Computed Hydrograph, 17^{th} Street Canal

The computed hydrograph (solid black line) obtained from the present model for the Orleans Avenue Canal is presented on Figure 4.136. From Figure 4.136, it is seen that the peak water surface elevation (WSE, so called water level in the IPET report) computed by the present model is approximately 4.39 m at the Orleans Avenue Canal site. Besides, it is seen that the peak water surface elevation induced by the Route 1-

traveling Hurricane Katrina with reduced forward speeds is much larger than the peak water surface level induced by the Route 1-travling Hurricane Katrina at the Orleans Avenue Canal site (4.39 m versus 3.27 m) after comparing the computed hydrograph made under the wind generated by the hurricane with the one made under the wind generated by the original Hurricane Katrina (see the solid red line on Figure 4.136). Therefore, it can be claimed that hurricane passing over Lake Pontchartrain with different forward speeds another route can cause a significant difference in water surface elevation although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

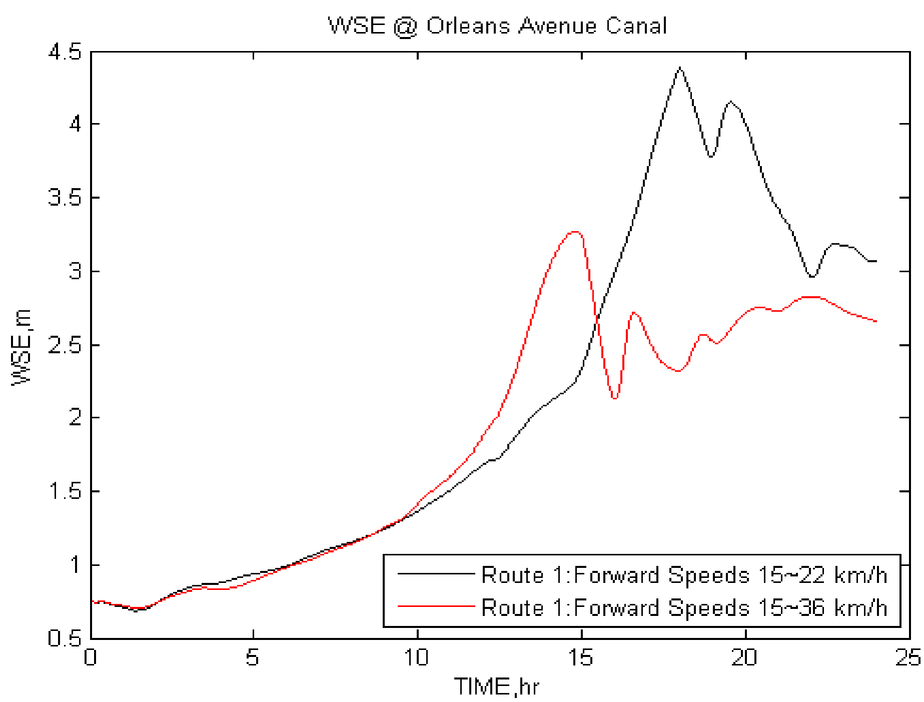

Figure 4.136 Computed Hydrograph, Orleans Avenue Canal

The computed hydrograph (solid black line) obtained from the present model for the London Avenue Canal is presented on Figure 4.137. From Figure 4.137, it is seen that the peak water surface elevation (WSE, so called water level in the IPET report) computed by the present model is approximately 4.40 m at the London Avenue Canal site. Besides, it is seen that the peak water surface elevation induced by the Route 1-traveling Hurricane Katrina with reduced forward speeds is much larger than the peak water surface level induced by the Route 1-traveling Hurricane Katrina at the London Avenue Canal site (4.40 m versus 3.30 m) after comparing the computed hydrograph made under the wind generated by the hurricane with the one made under the wind generated by the original Hurricane Katrina (see the solid red line on Figure 4.137). Therefore, it can be claimed that this evident difference in water surface elevation is caused by a hurricane passing over Lake Pontchartrain with different forward speeds although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

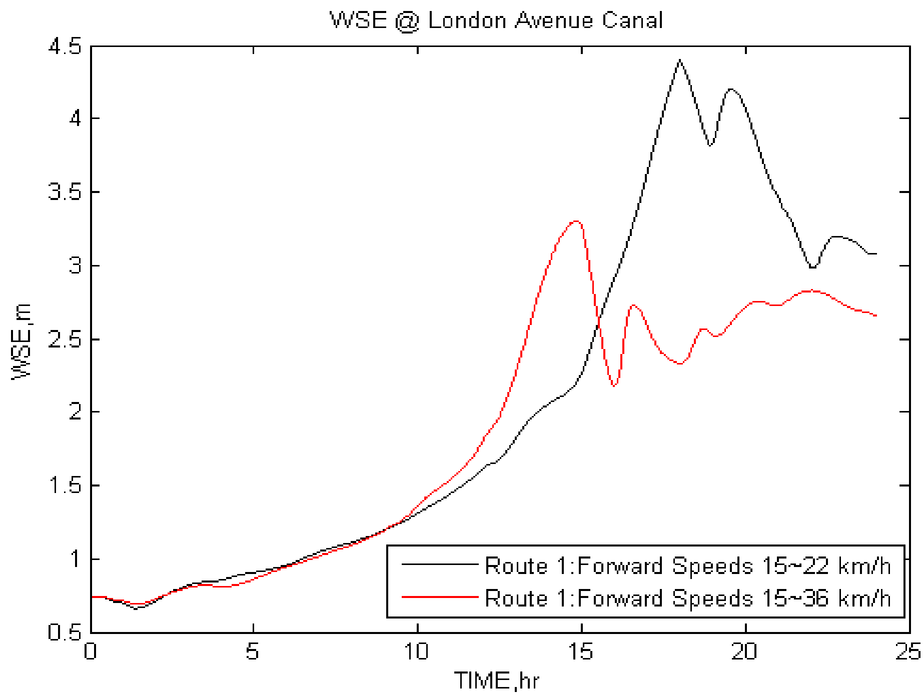

Figure 4.137 Computed Hydrograph, London Avenue Canal

The computed hydrograph (solid black line) obtained from the present model for the IHNC-Lakefront Airport is presented on Figure 4.138. From Figure 4.138, it is seen that the peak water surface elevation (WSE, so called water level in the IPET report) computed by the present model is approximately 4.33 m at the IHNC-Lakefront Airport site. Besides, it is seen that the peak water surface elevation induced by the Route 1-traveling Hurricane Katrina with reduced forward speeds is much larger than the peak water surface level induced by the Route 1-traveling Hurricane Katrina at the IHNC-Lakefront Airport site (4.33 m versus 3.30 m) after comparing the computed hydrograph made under the wind generated by the hurricane with the one made under the wind generated by the Route 1-traveling Hurricane Katrina (see the solid red line on Figure

4.138). Therefore, it can be claimed that hurricane passing over Lake Pontchartrain with different forward speeds can cause an evident difference in water surface elevation although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

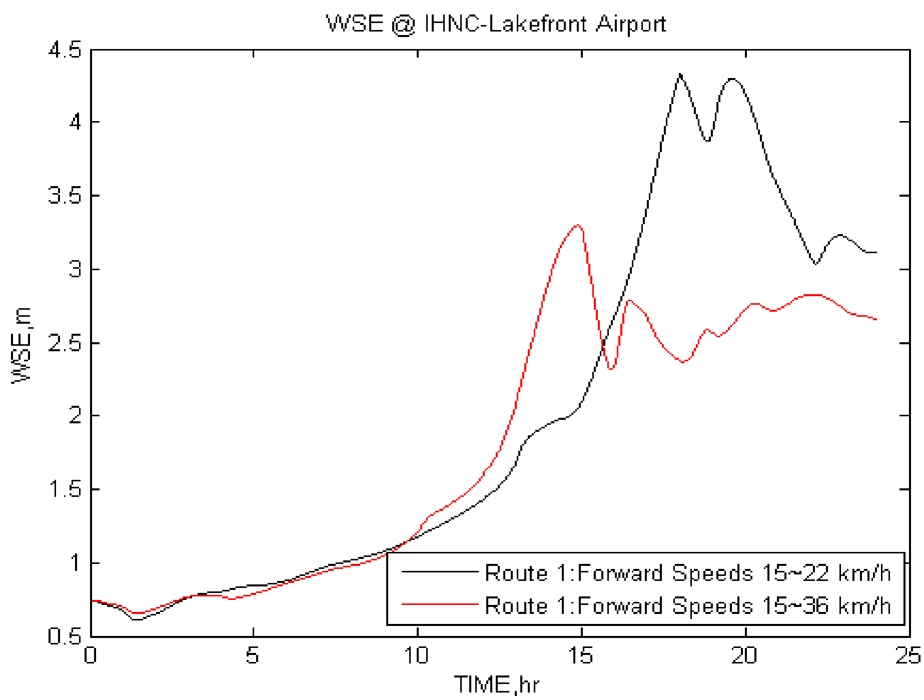

Figure 4.138 Computed Hydrograph, IHNC-Lakefront Airport

The computed hydrograph (solid black line) obtained from the present model for the Midlake is presented on Figure 4.139. From Figure 4.139, it is seen that the peak water surface elevation induced by the Route 1-traveling Hurricane Katrina with reduced forward speeds is much larger than the peak water surface level induced by the Route 1-traveling Hurricane Katrina at the Midlake site after comparing the computed hydrograph made under the wind generated by the hurricane with the one made under the wind generated by the Route 1-traveling Hurricane Katrina (see the solid red line on Figure 4.139). Furthermore, the general trend of the rise and fall of water level induced by the wind generated by the Route 1-traveling Hurricane Katrina with reduced forward speeds is slightly different from the general trend of the rise and fall of water level induced by the wind generated by the Route 1-traveling Hurricane Katrina. Therefore, it can be claimed that these evident differences in the water surface elevations are caused by a hurricane passing over Lake Pontchartrain with different forward speeds although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

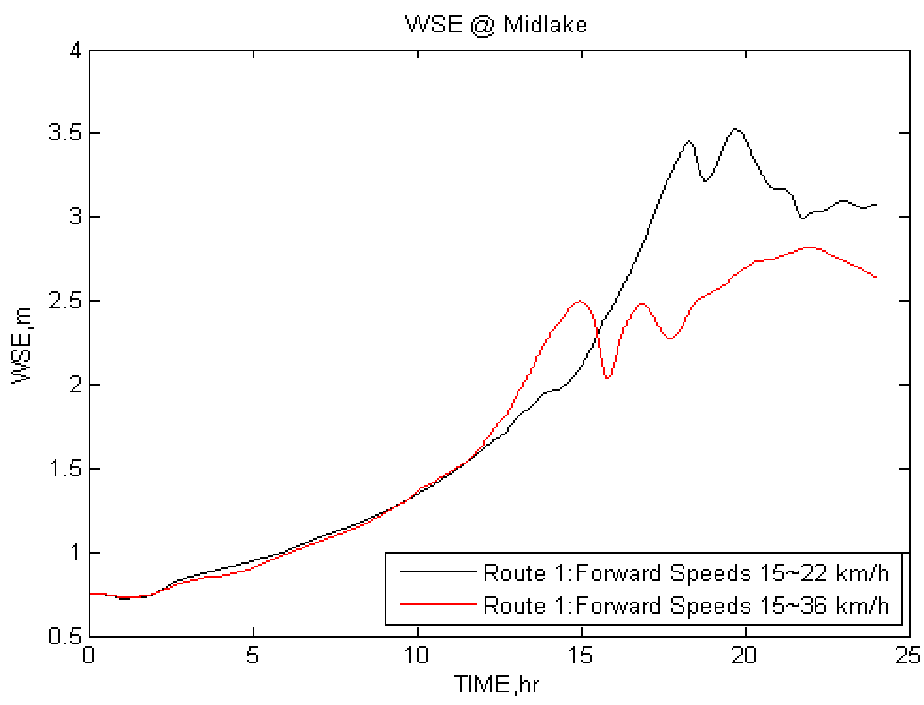

Figure 4.139 Computed Hydrograph, Midlake

The computed hydrograph (solid black line) obtained from the present model for Bayou La Branche (named Bayou Labranch in the IPET report) is presented on Figure 4.140. It can be seen from Figures 4.7 and 4.13 that Bayou La Branche is in the swamp along the southwest shore of Lake Pontchartrain and the swamps along the entire southwest shore of Lake Pontchatrain have been assigned into the computational domain for the current numerical simulations performed by the FVM model. From Figure 4.140, it is seen that the peak water surface elevation induced by the Route 1-traveling Hurricane Katrina with reduced forward speeds is much larger than the peak water surface level induced by the Route 1-traveling Hurricane Katrina at Bayou La Branche site after comparing the computed hydrograph made under the wind generated by the hurricane with the one made under the wind generated by the Route 1-traveling Hurricane Katrina (see the solid red line on Figure 4.140); besides, the moments at which the highest water surface elevations induced by the winds generated by two hurricanes (Route 1-traveling Katrina with reduced forward speeds and Route 1-traveling Katrina) happen at Bayou La Branche site are not within the same period of time. Furthermore, the general trends of the rise and fall of water levels on both computed hydrographs (solid black and solid red lines on Figure 4.140) made by the present model are completely different at Bayou La Branche site. Therefore, it can be claimed that these evident differences in the water surface elevation are caused by a hurricane passing over Lake Pontchartrain with different forward speeds although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

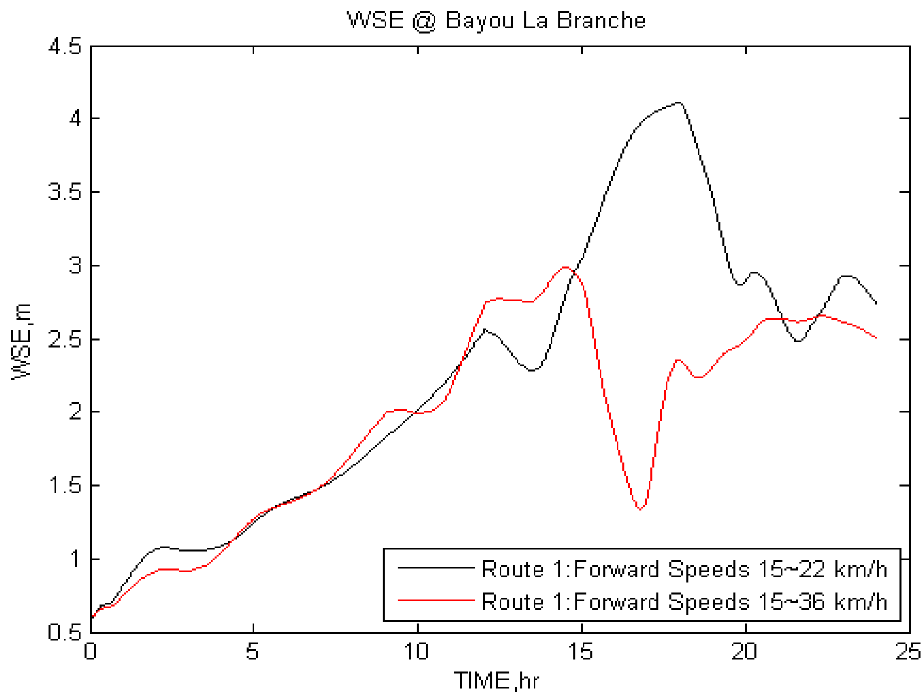

Figure 4.140 Computed Hydrograph, Bayou La Branche

The computed hydrograph (solid black line) obtained from the present model for Pass Manchac-Turtle Cove is presented on Figure 4.141. From Figures 4.7 and 4.13, it can be seen that Pass Manchac is a the narrow strip of water connecting Lake Pontchartrain and Lake Maurepas and the entire Pass Manchac is included in the computational domain used in the current numerical simulations performed by the present model. From Figure 4.141, it is seen that the peak water surface elevation induced by the Route 1-traveling Hurricane Katrina with reduced forward speeds is almost equal to the peak water surface level induced by the Route 1-traveling Hurricane Katrina at Pass Manchac-Turtle Cove site after comparing the computed hydrograph made under the wind generated by the hurricane with the one made under the wind generated by the Route 1-traveling

Hurricane Katrina (see the solid red line on Figure 4.141); however, the moments at which the highest water surface elevations induced by the winds generated by two hurricanes (Route 1-traveling Katrina with reduced moving speeds and Route 1-traveling Katrina) happen at Pass Manchac-Turtle Cove site are not within the same period of time. Besides, the general trends of the rise and fall of water levels on both computed hydrographs (solid black and solid red lines on Figure 4.141) made by the present model are entirely different at Pass Manchac-Turtle Cove site. Therefore, it can be claimed that these evident differences in the water surface elevation are caused by a hurricane passing over Lake Pontchartrain with different forward speeds although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

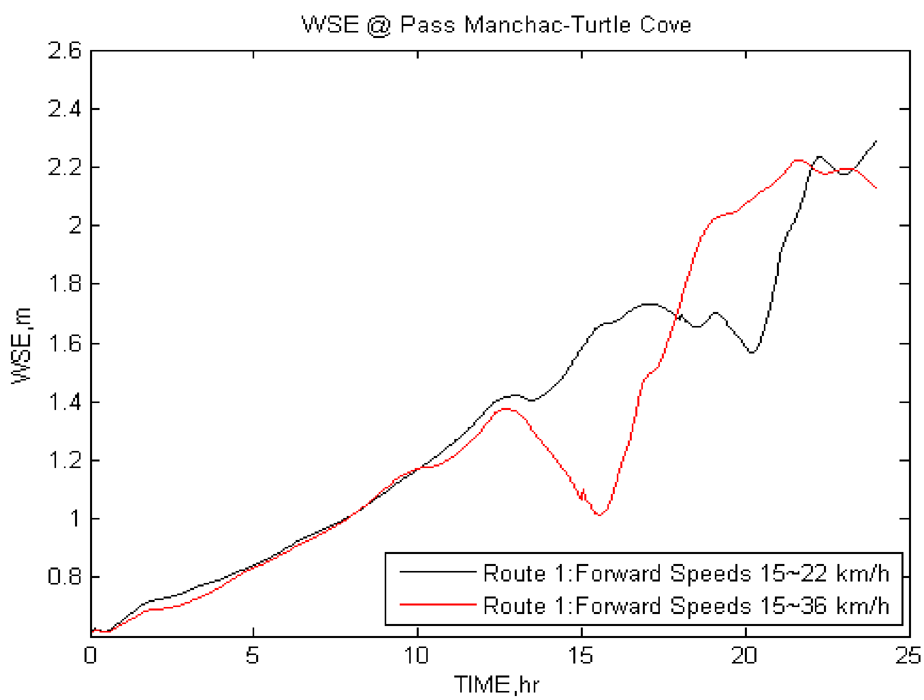

Figure 4.141 Computed Hydrograph, Pass Manchac-Turtle Cove

The computed hydrograph (solid black line) obtained from the present model for Little Irish Bayou is presented on Figure 4.142. From Figure 4.142, it is seen that the peak water surface elevation induced by the Route 1-traveling Hurricane Katrina with reduced forward speeds is much larger than the peak water surface level induced by the Route 1-traveling Hurricane Katrina at Little Irish Bayou site after comparing the computed hydrograph made under the wind generated by the hurricane with the one made under the wind generated by the Route 1-traveling Hurricane Katrina (see the solid red line on Figure 4.142). Besides, the general trends of the rise and fall of water levels on both computed hydrographs (solid black and solid red lines on Figure 4.142) made by the present model are almost identical although the moments at which the highest water surface elevations induced by the winds generated by two hurricanes (Route 1-traveling Katrina with reduced forward speeds and Route 1-traeling Katrina) happen at Little Irish Bayou site are not within the same period of time. Therefore, it can be claimed that these evident differences in the water surface elevation are caused by a hurricane passing over Lake Pontchartrain with different forward speeds although the strength (pressure and wind speed) of the simulated Hurricane Katrina is identical to the original one.

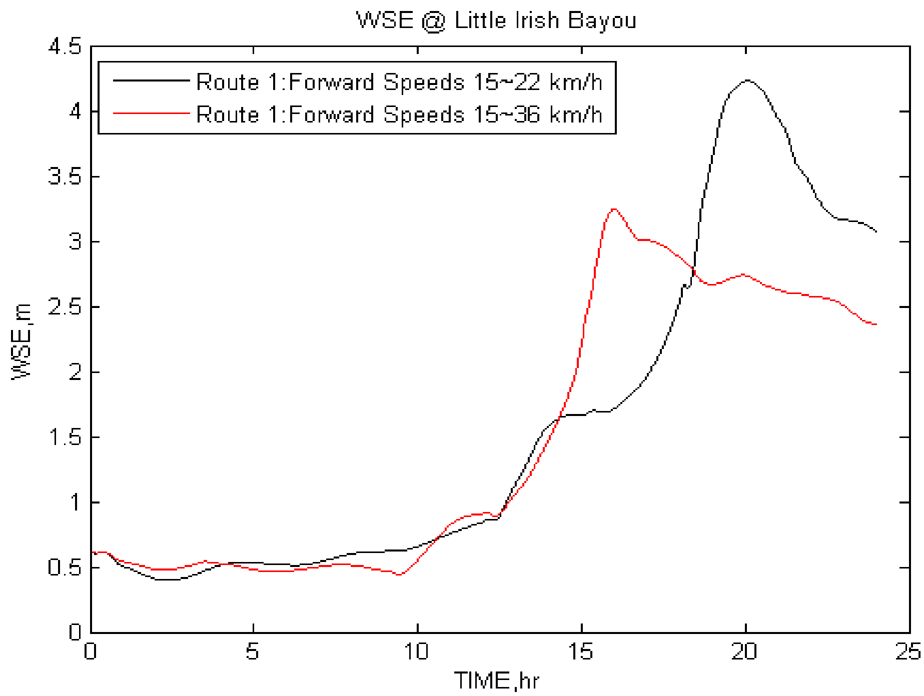

Figure 4.142 Computed Hydrograph, Little Irish Bayou

The computed hydrographs of the water surface elevation (WSE) showing on S-N and W-E cross-sections of Lake Pontchartrain induced by the wind generated through the Route 1 –Traveling Hurricane Katrina with reduced forward speeds (see Figure 4.28) are presented on Figures 4.143 and 4.144, respectively. It is seen from Figures 4.143 and 4.144 that the wind-induced oscillations in Lake Pontchartrain are the evident phenomena as the Hurricane Katrina with reduced forward speeds progressed over the Southeast Louisiana region (Route 1 shown in Figure 4.28). In the following paragraphs, the hourly contour maps of the water surface elevation (WSE) for the entire Lake Pontchartrain, as the Hurricane Katrina with reduced forward speeds progressed over the Southeast Louisiana region (Route 1 shown in Figure 4.28), are used to investigate the oscillations of semi-enclosed water body induced by hurricanes under specific routes and different forward speeds.

The hourly contour maps of the computed water surface elevation (WSE) for the entire Lake Pontchartrain induced by the wind generated through the Route 1-traveling Hurricane Katrina with reduced forward speeds are presented from Figures 4.145 to Figures 4.169. The time-frame of these contour maps is from 12:00 am UTC August 29, 2005 to 12:00 am UTC August 30, 2005. It is assigned that $t = 0$ is at 11:59:15 pm UTC August 28, 2005 and consequently the reference WSE at $t = 0$ is zero. Therefore, the oscillation phenomenon is not evident throughout entire Lake Pontchartrain at the starting moment of the numerical simulation (12:00 am August 29, 2005), as it is seen from Figure 4.145. Because the Route 1-traveling Hurricane Katrina with reduced forward speeds might make its first landfall around 8:40 am CDT (13:40 am UTC) August 29 at Southeast Louisiana and the oscillation induced by tides from Gulf of Mexico into Lake Pontchartrain is not an influential factor in this study, this is a reasonable assumption that the oscillations in Lake Pontchartrain induced by wind generated by the Route 1-traveling Hurricane Katrina with reduced forward speeds can be focused on the 24-hours period between 12:00 am UTC August 29, 2005 and 12:00 am UTC August 30, 2005.

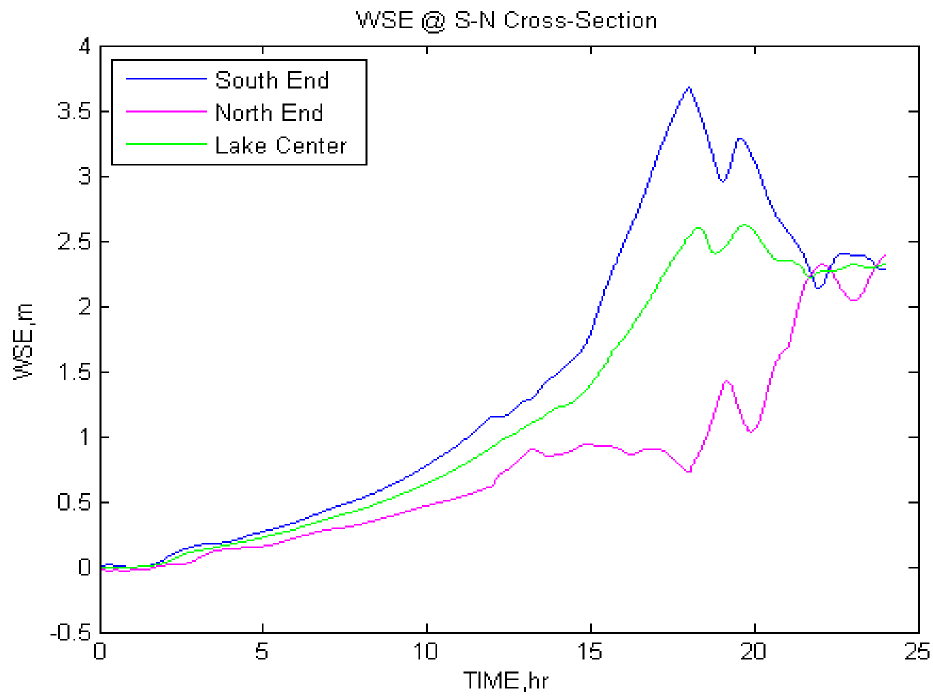

Figure 4.143 Hydrographs of the S-N cross-section

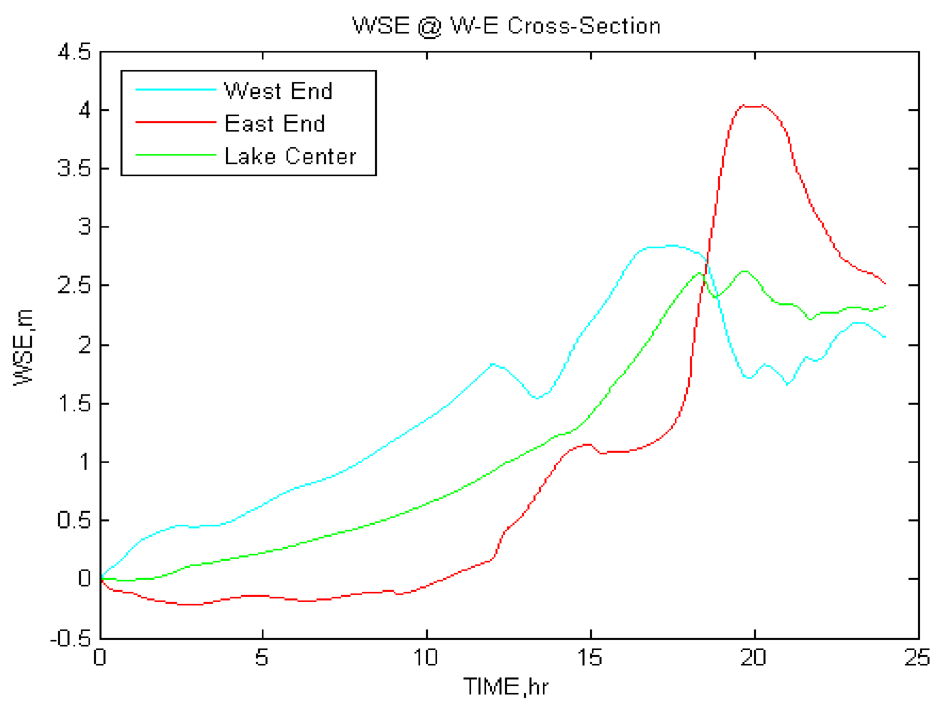

Figure 4.144 Hydrographs of the W-E cross-section

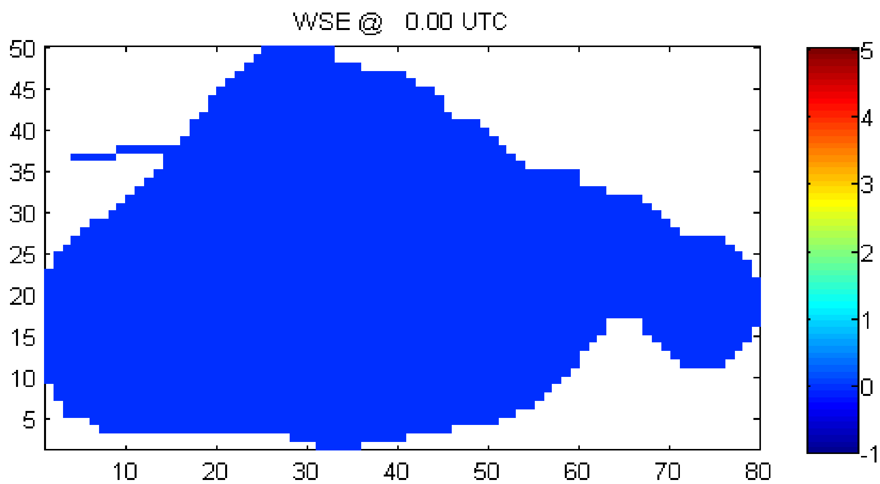

Figure 4.145 Contours of WSE at 12:00 am (UTC) August 29, 2005

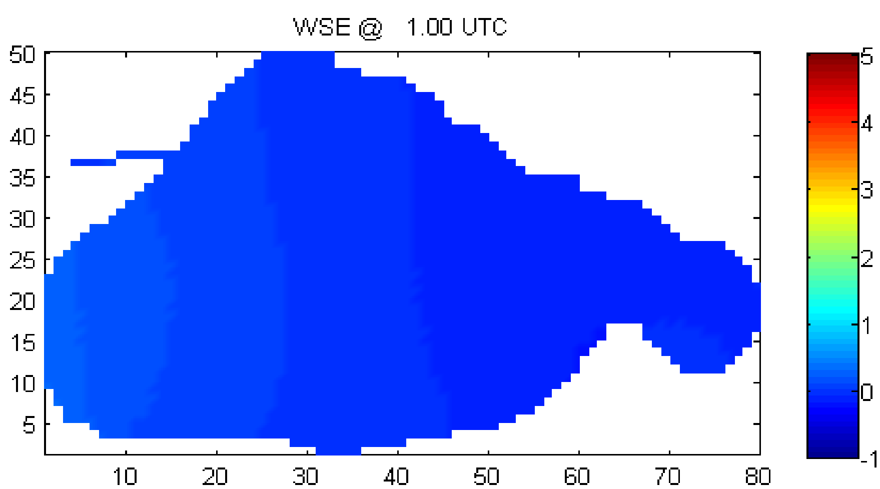

Figure 4.146 Contours of WSE at 01:00 am (UTC) August 29, 2005

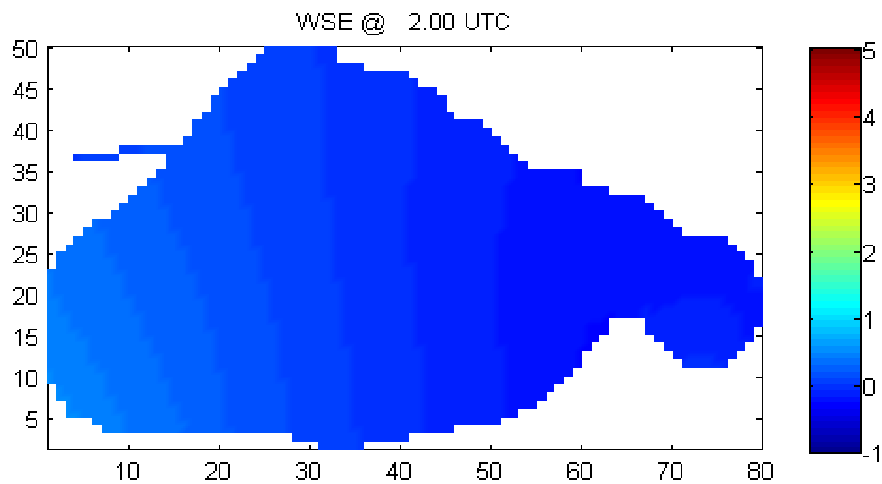

Figure 4.147 Contours of WSE at 02:00 am (UTC) August 29, 2005

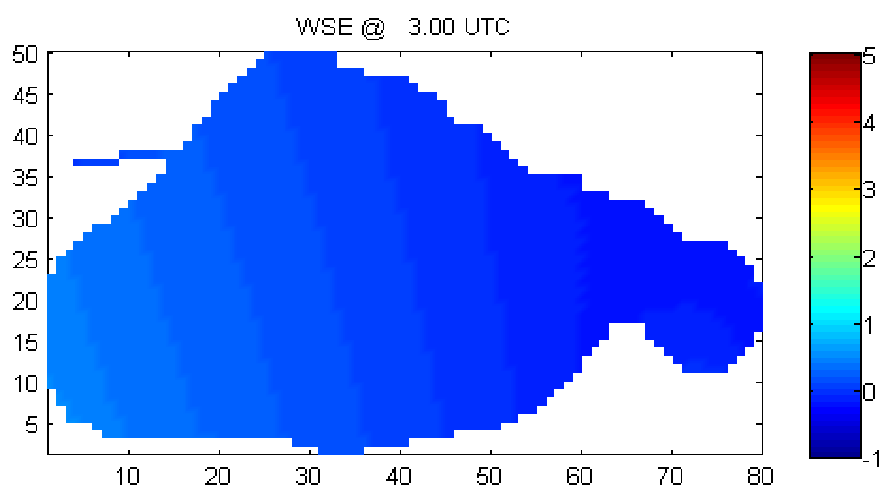

Figure 4.148 Contours of WSE at 03:00 am (UTC) August 29, 2005

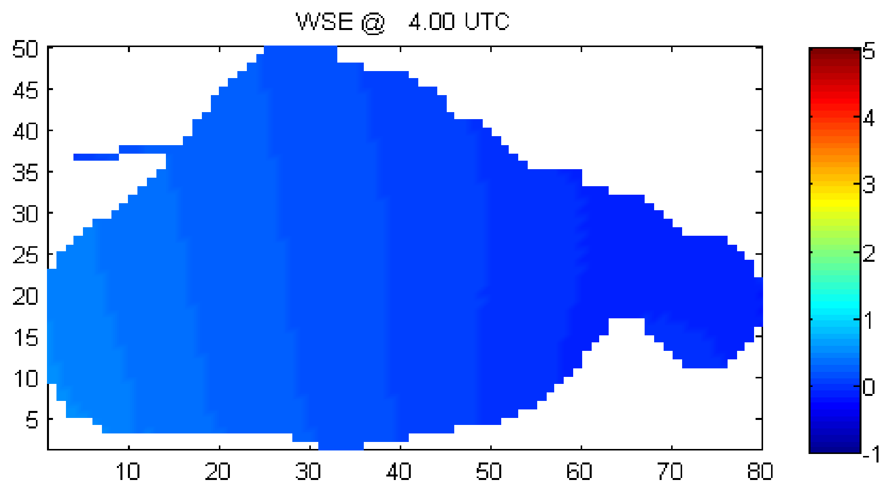

Figure 4.149 Contours of WSE at 04:00 am (UTC) August 29, 2005

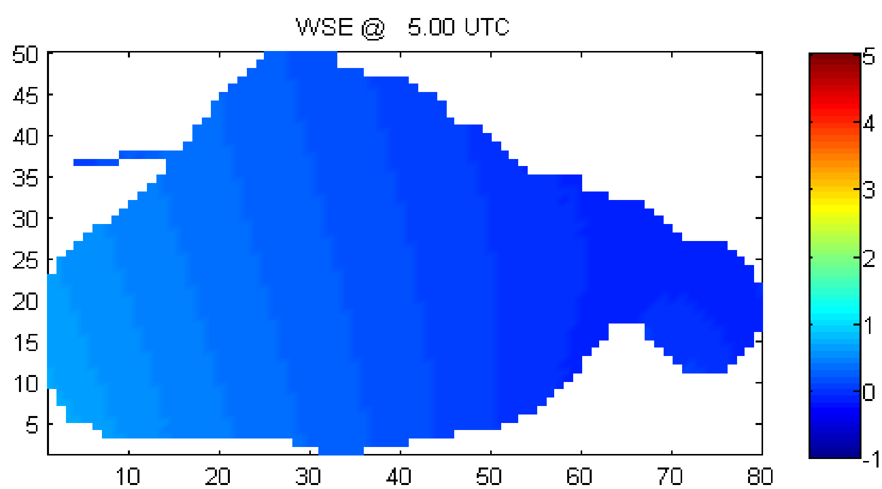

Figure 4.150 Contours of WSE at 05:00 am (UTC) August 29, 2005

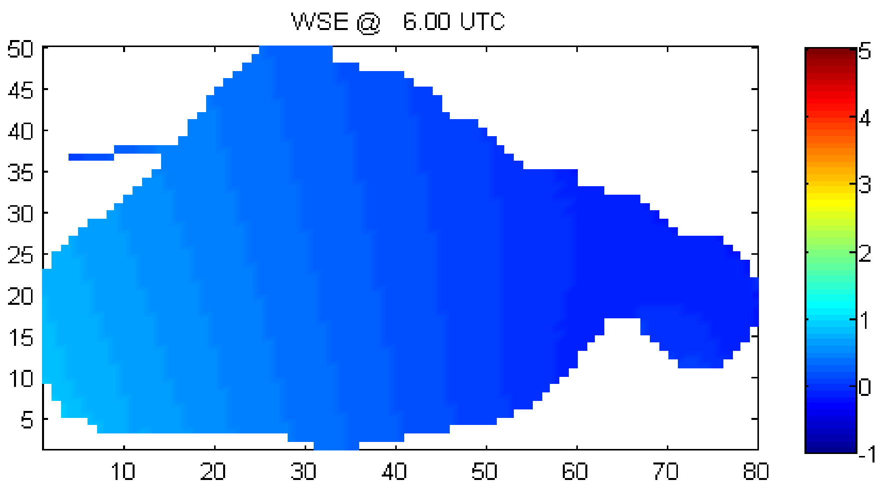

Figure 4.151 Contours of WSE at 06:00 am (UTC) August 29, 2005

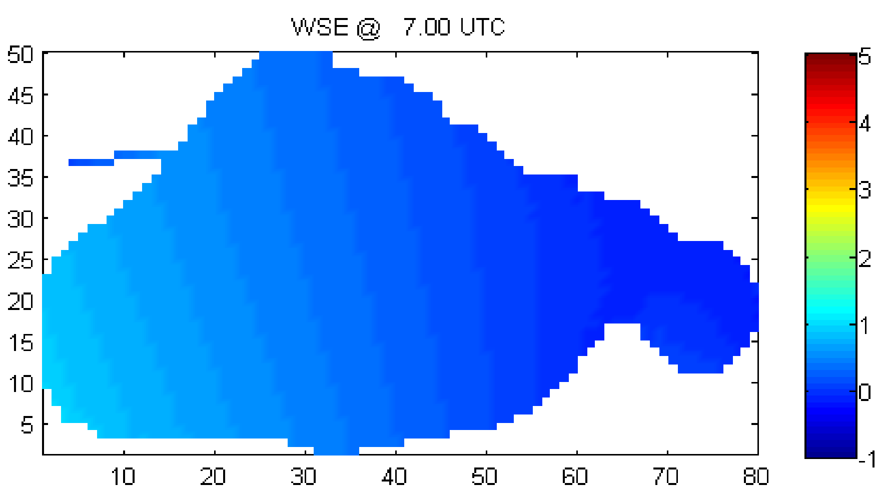

Figure 4.152 Contours of WSE at 07:00 am (UTC) August 29, 2005

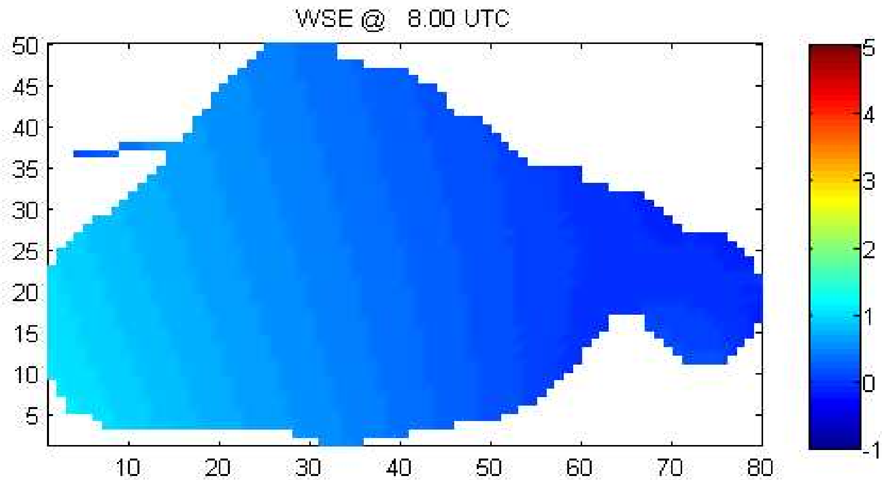

Figure 4.153 Contours of WSE at 08:00 am (UTC) August 29, 2005

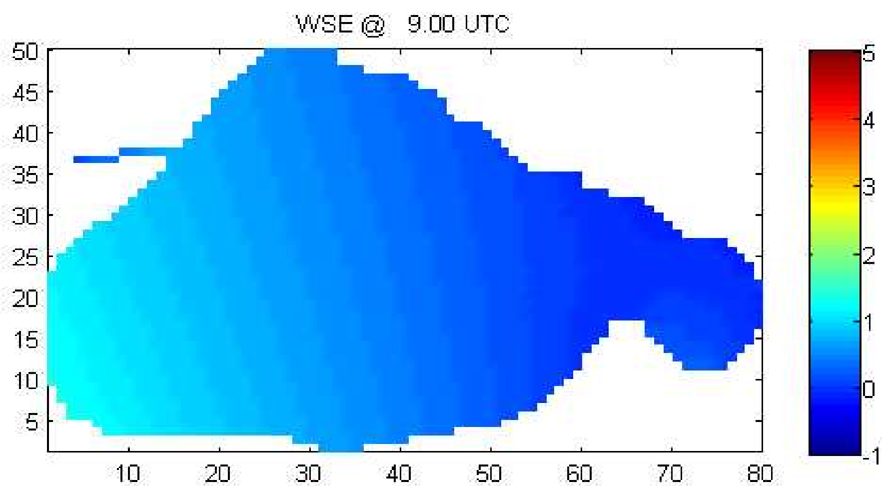

Figure 4.154 Contours of WSE at 09:00 am (UTC) August 29, 2005

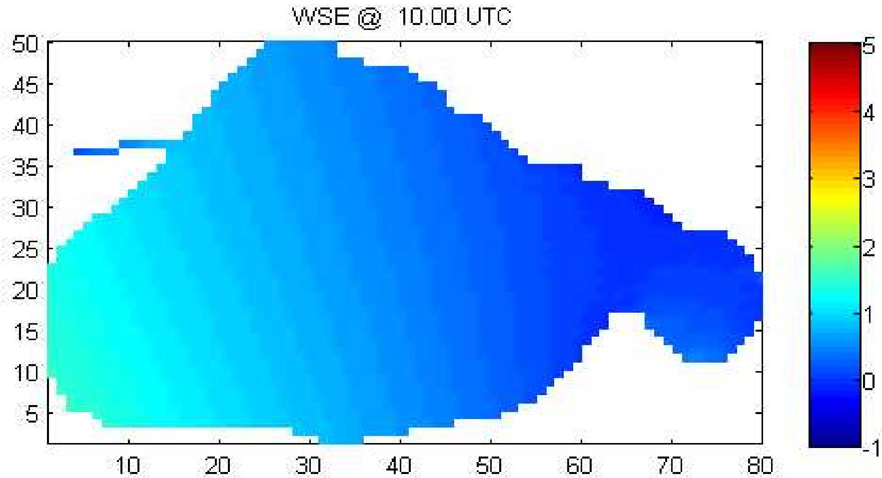

Figure 4.155 Contours of WSE at 10:00 am (UTC) August 29, 2005

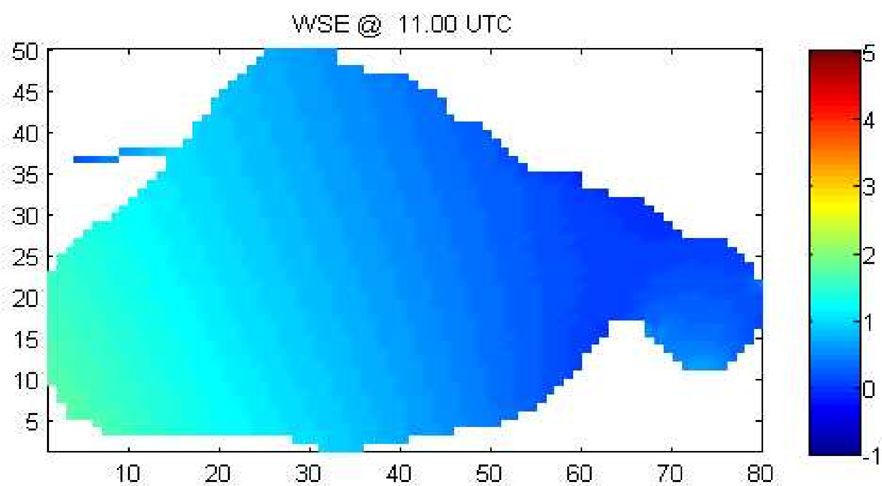

Figure 4.156 Contours of WSE at 11:00 am (UTC) August 29, 2005

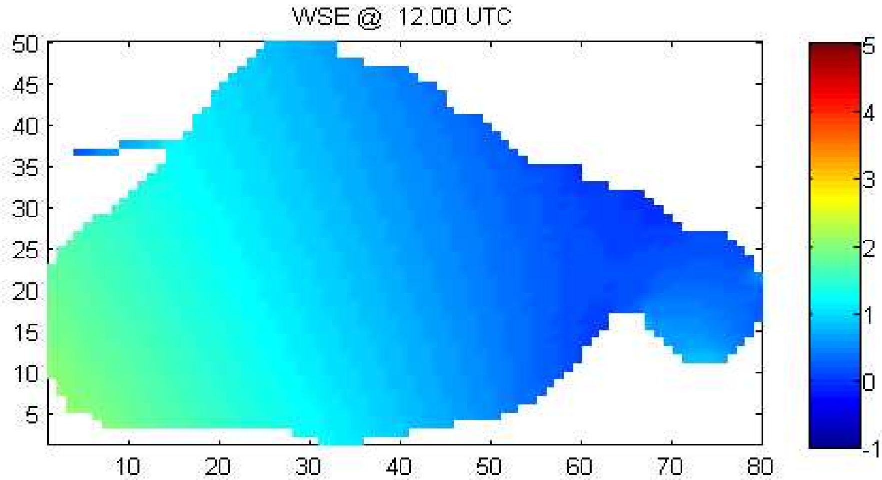

Figure 4.157 Contours of WSE at 12:00 pm (UTC) August 29, 2005

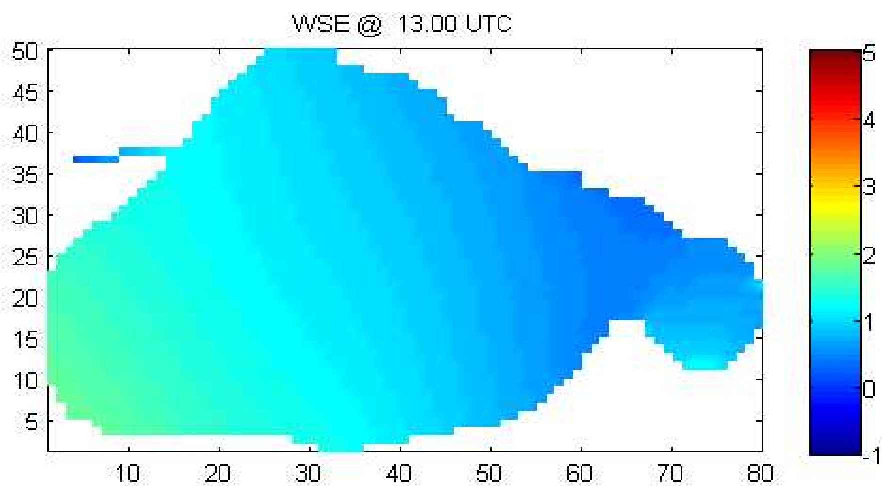

Figure 4.158 Contours of WSE at 01:00 pm (UTC) August 29, 2005

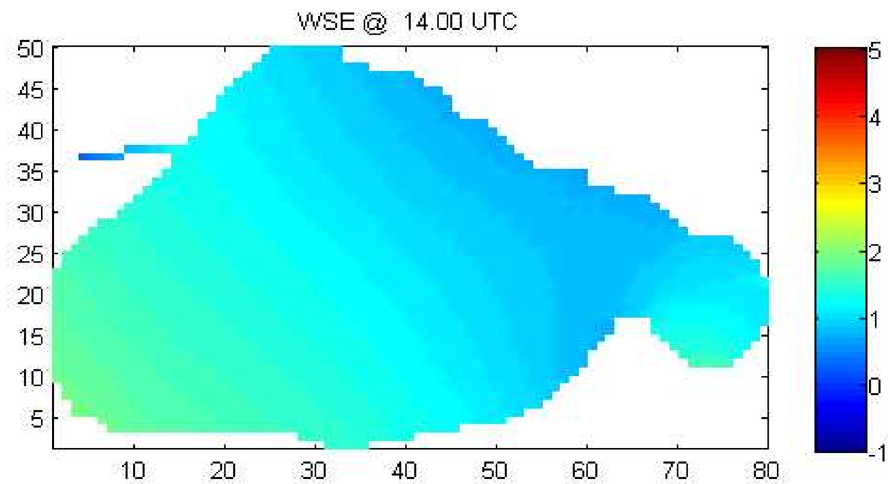

Figure 4.159 Contours of WSE at 02:00 pm (UTC) August 29, 2005

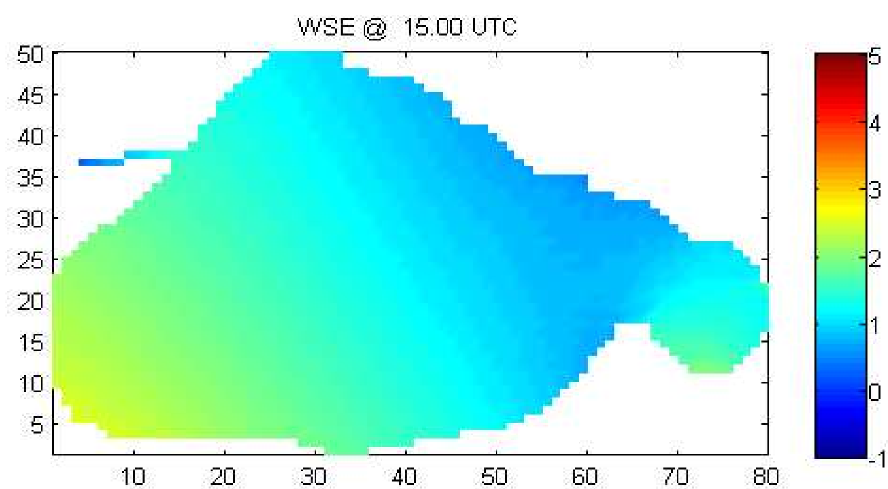

Figure 4.160 Contours of WSE at 03:00 pm (UTC) August 29, 2005

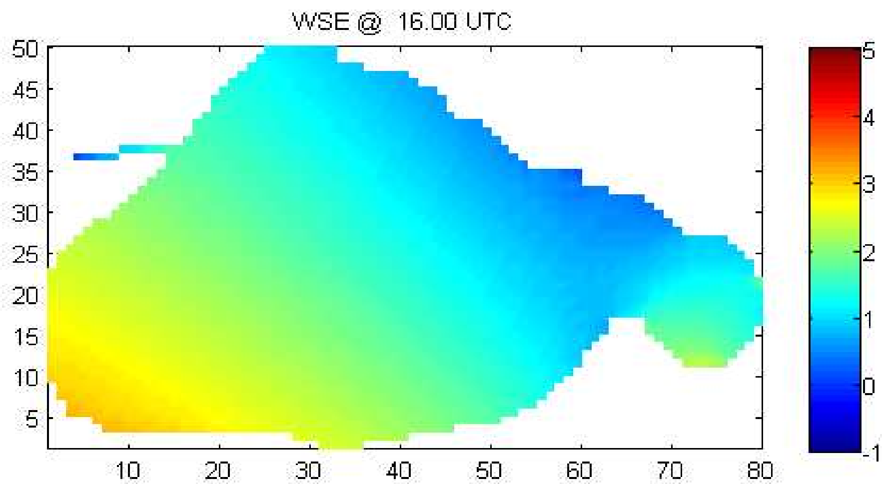

Figure 4.161 Contours of WSE at 04:00 pm (UTC) August 29, 2005

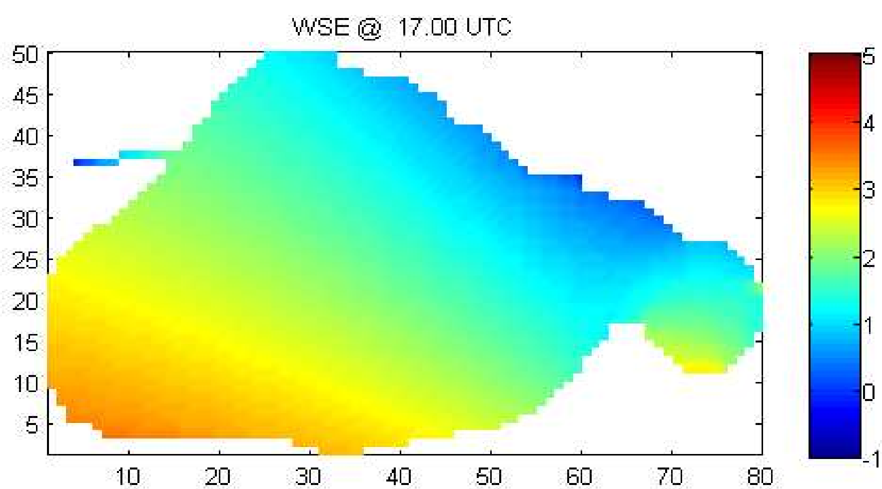

Figure 4.162 Contours of WSE at 05:00 pm (UTC) August 29, 2005

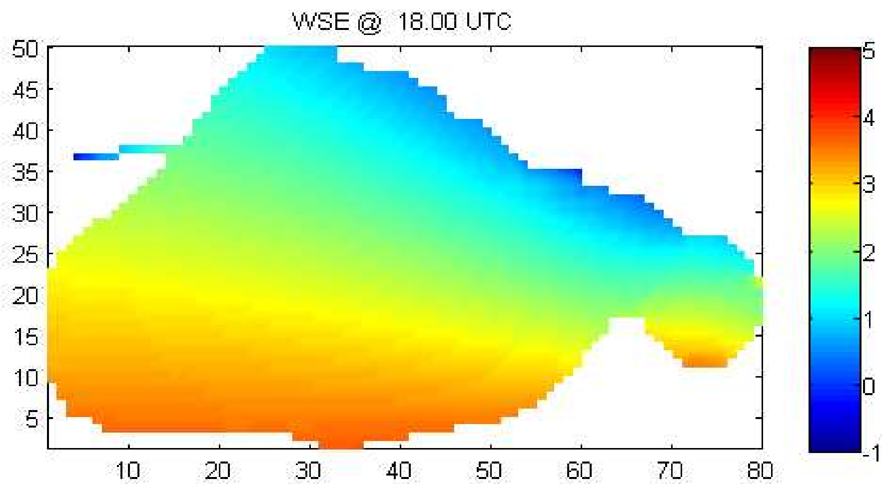

Figure 4.163 Contours of WSE at 06:00 pm (UTC) August 29, 2005

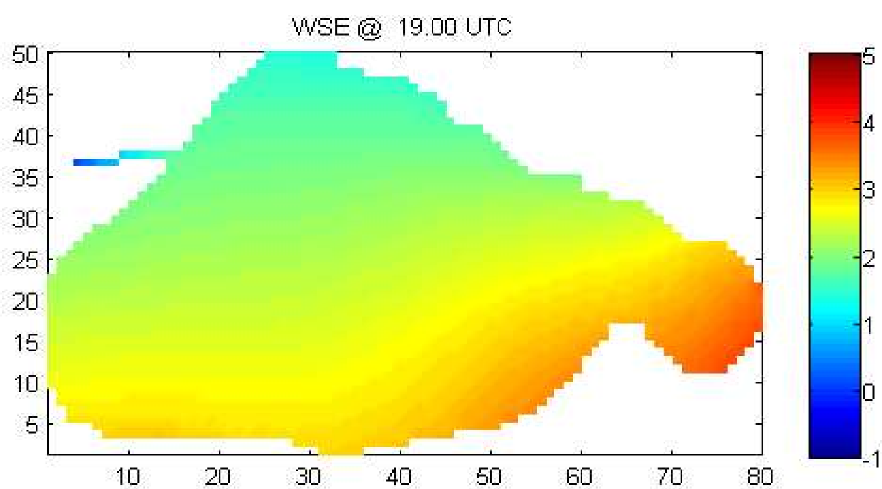

Figure 4.164 Contours of WSE at 07:00 pm (UTC) August 29, 2005

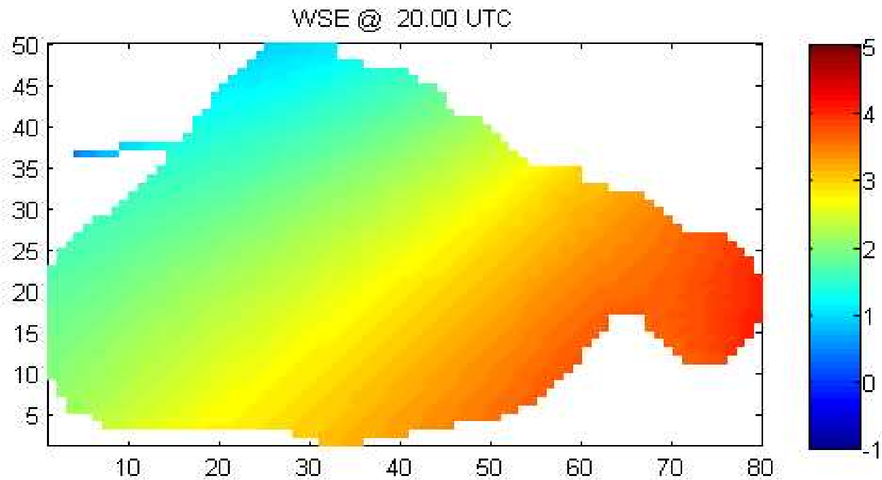

Figure 4.165 Contours of WSE at 08:00 pm (UTC) August 29, 2005

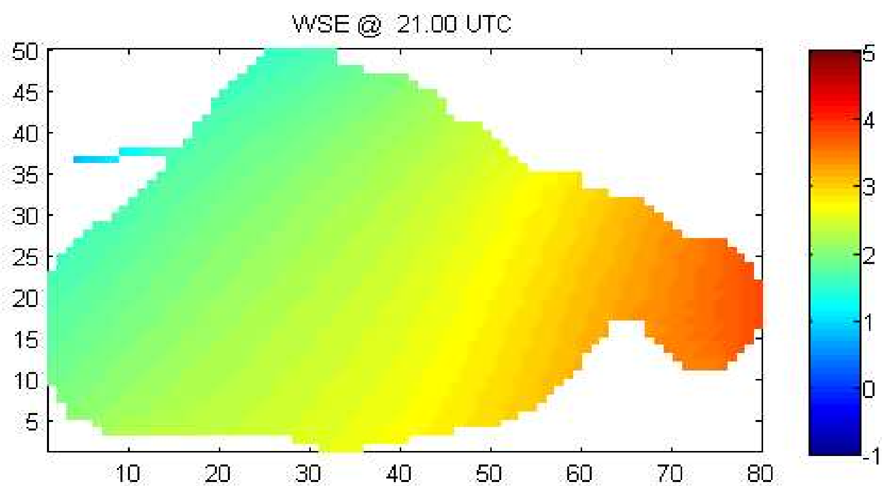

Figure 4.166 Contours of WSE at 09:00 pm (UTC) August 29, 2005

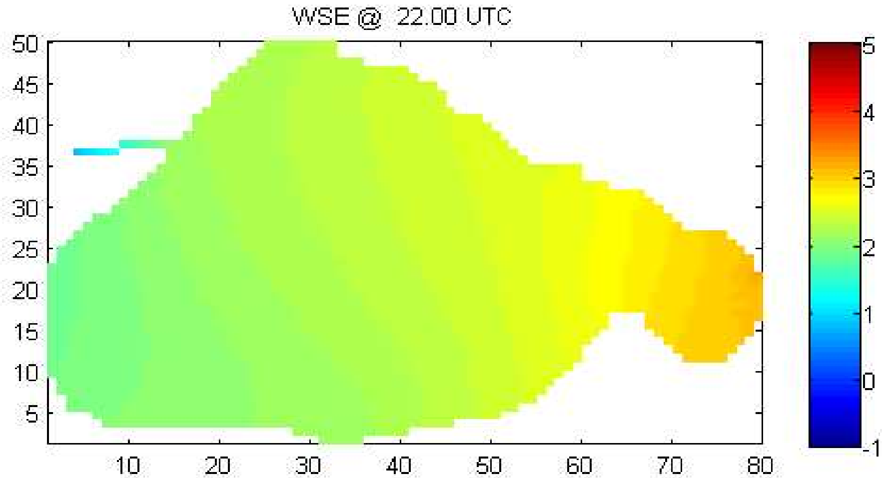

Figure 4.167 Contours of WSE at 10:00 pm (UTC) August 29, 2005

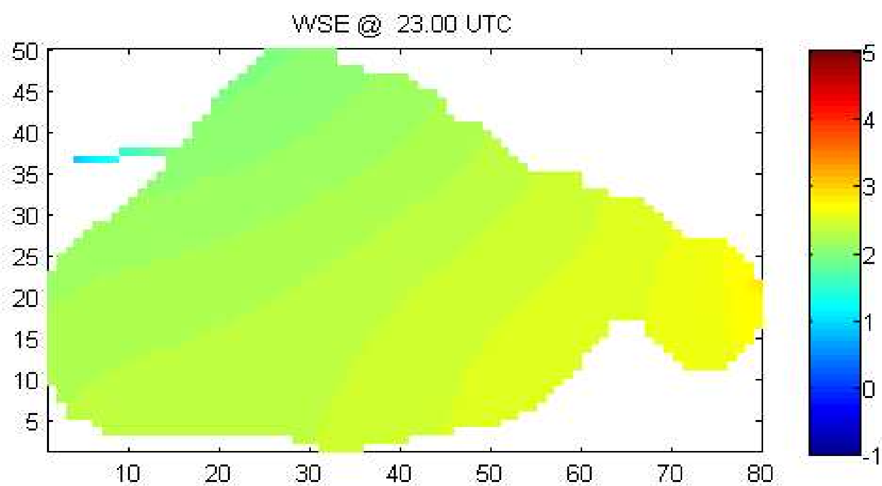

Figure 4.168 Contours of WSE at 11:00 pm (UTC) August 29, 2005

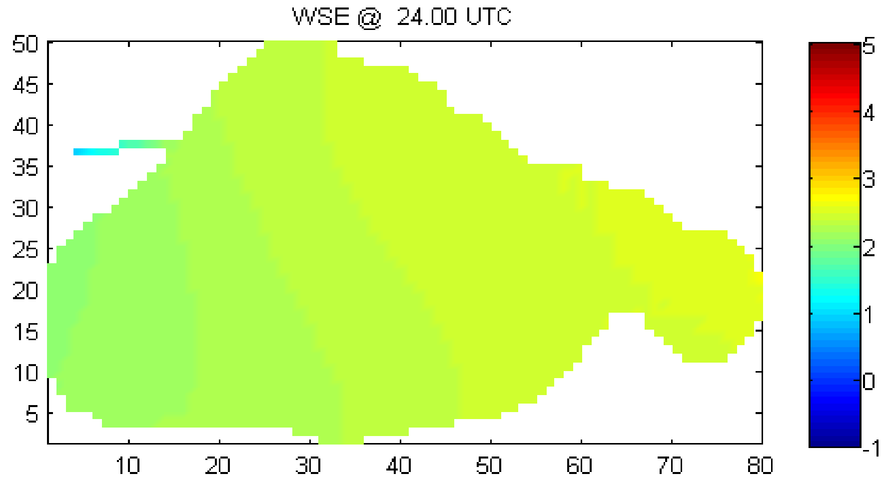

Figure 4.169 Contours of WSE at 12:00 am (UTC) August 30, 2005

It can be seen from Figures 4.146 to 4.151 that the oscillation in Lake Pontchartrain is built up as the Route 1-traveling Hurricane Katrina with reduced forward speeds approaches to Southeast Louisiana and it becomes more obvious as time goes by. It is very evident that the direction of node line ($\eta = 0$) in the lake is in the North-South orientation. It is seen that the water in the east part of the lake is driven by the wind to the west part of the lake during the first 6-hour period, as we examine the temporal variations of the contours of WSE from 12:00 to 06:00 am UTC August 29, 2005. The strength of the Route 1-traveling Hurricane Katrina with reduced forward speeds remains Category 4 in Saffir-Simpson Scale within this 6-hours period.

As the Route 1-traveling Hurricane Katrina with reduced forward speeds approaches to Southeast Louisiana, the magnitude of oscillation in the lake gradually increases between 07:00 am UTC and 12:00 pm UTC August 29, 2005. During this 6-hours period, the direction of node line ($\eta = 0$) in the lake slowly changes from the North-South orientation to the Northwest-Southeast orientation since the direction of the dominant wind alters as the hurricane approaches to Lake Pontchartrain; meanwhile, the strength of the hurricane is gradually reducing from Category 4 to 3 in Saffir-Simpson Scale. We can see these phenomena after examining the temporal variations of the contours of WSE from Figures 4.152 to 4.157.

From 12:00 pm UTC to 03:00 pm UTC August 29, the Route 1-traveling Hurricane Katrina with reduced forward speeds approaches to Southeast Louisiana and might make its first landfall at approximately 13:40 pm UTC (8:40 am Local Time); meanwhile, the strength of the Route 1-traveling Hurricane Katrina with reduced forward speeds still remains Category 3. Thus, the magnitude of oscillation in the lake evidently increases as it is compared with the oscillations happened in the lake during the previous 12 hours. It is seen from Figures 4.158 to 4.160 that the direction of node line ($\eta = 0$) in the lake remains in the Northwest-Southeast orientation although the direction of the dominant wind rapidly alters in a counterclockwise pattern during this 3-hours period.

During the next 3-hours period (from 03:00 to 06:00 pm UTC August 29), Hurricane Katrina passes nearby the east shore and its surrounding regions of Lake Pontchartrain.

Thus, this close-encounter between the hurricane and the lake causes significant oscillations in Lake Pontchartrain as we compare the oscillations happened in the lake during the previous 15 hours. It is seen from Figures 4.161 to 4.163 that the direction of node line ($\eta = 0$) in the lake changes from the Northwest-Southeast orientation to the West-East orientation as the direction of the dominant wind rapidly alters during this 3-hours period. Meanwhile, the magnitude of oscillation (the height of WSE) becomes higher than the previous 3 hours, and the oscillation along the south shore of Lake Pontchartrain reaches the highest magnitude around 06:00 pm UTC (1:00 pm Local Time), as we have already seen from Figures 4.161 to 4.163. Within this 3-hours period, the Route 1-traveling Hurricane Katrina with reduced forward speeds still remains Category 3.

From 06:00 pm UTC to 09:00 pm UTC August 29, the Route 1-traveling Hurricane Katrina with reduced forward speeds continuously moves inland with a north direction and might make its second landfall at approximately 06:40 pm UTC (01:40 pm Local Time) near Louisiana/Mississippi border; meanwhile, the strength of the Route 1-traveling Hurricane Katrina with reduced forward speeds still remains Category 3. It is seen from Figures 4.164 to 4.166 that the direction of node line ($\eta = 0$) changes from the West-East orientation to the Southwest-Northeast orientation as the direction of the dominant wind rapidly alters in a counterclockwise pattern during this 3-hours period. Because the surge propagates into Lake Pontchartrain from the Gulf of Mexico via Lake Borgne (see Figure 4.3), a huge amount of water flows into Lake Pontchartrain and the magnitude of oscillation (the height of WSE) in Lake Pontchartrain evidently increases even though the hurricane leaves the central and northeast regions of the lake. Furthermore, the node line ($\eta = 0$) disappears and the WSE in the entire lake is greater than the reference WSE ($\eta = 0$) from 07:00 pm, as it is seen from Figure 4.164.

In the final 3-hours period (from 10:00 pm UTC on August 29 to 12:00 am UTC August 30, 2005), the strength of the Route 1-traveling Hurricane Katrina with reduced forward speeds gradually weakens from Category 3 to 2 and finally the hurricane moves inwardly into the northeastern region of the United States of America as the original Hurricane Katrina moves inwardly (see Figures 4.2 and 4.28). Although the direction of dominant wind keeps turning counterclockwise during this 3-hours period, the wind generated by the hurricane is evidently weaker than it was in the previous 21-hours period. Since the hurricane moves away from the lake, the magnitude of oscillation in Lake Pontchartrain drastically reduces and is much smaller than it was in the previous 3-hour period. Besides, the major sloshing motion is moving toward the east within this 3-hours period. The WSE in the lake significantly recede although there is not enough wind stress to drive out the water from Lake Pontchartrain to Lake Borgne and other surrounding water bodies (for example, Lake Maurepas); meanwhile, the WSE in the entire lake remains greater than the reference WSE ($\eta = 0$) in this 3-hours period. Besides, there is a significant drawdown in the east portion of Lake Pontchartrain at the finale of the numerical simulation (10:00 pm August 29 to 12:00 am August 30, 2005) as it is seen from Figures 4.167 to 4.169. We can obtain these discoveries by examining the temporal variations of WSE from Figures 4.164 to 4.169. Furthermore, the significant findings drawn from these hourly contour maps (from Figures 4.145 to 4.169) are summarized in the following paragraphs.

The Route 1-traveling Hurricane Katrina with reduced forward speeds moves in a nearly north direction and passes through the regions nearby the east shore of Lake Pontchartrain between 12:00 am UTC August 29, 2005 and 12:00 am UTC August 30, 2005 corresponding to the entire 24-hours of the numerical simulations made by the present model. The closest encounter between the Route 1-traveling Hurricane Katrina with reduced forward speeds and Lake Pontchartrain takes place between 03:00 pm UTC August 29, 2005 and 12:00 am UTC August 30, 2005 (or between 10:00 am and 7:00 pm Local Time). During this 9-hours period, there are three significant factors of the hurricane needed to be reviewed:

1. The hurricane remains Category 3 intensity of Saffir-Simpson Scale until 21:00 pm UTC (16:00 pm Local Time), after which the strength of the hurricane gradually reduces to Category 2.
2. The hurricane is moving in a nearly north direction with an approximate speed of 19 to 22 km/hr.
3. The distance between the eye of the hurricane and the east shore of the lake is approximately 12 km.

Because of these three unique characteristics of the interaction between the hurricane and the lake, the sloshing motion of the lake water surface changes in a counterclockwise pattern in the lake as the hurricane itself rotates in the counterclockwise character. In detail, the dominant sloshing motion at Lake Pontchartrain turns from the southwest to the east within this 9-hours period. During this 9-hours, the highest amplitude of oscillation (maximum WSE) along the south shore of the lake happens around 06:00 pm UTC (1:00 pm Local Time) with a magnitude of 4.33 m to 4.45 m predicted by the present model

Furthermore, the moving direction of the storm surge gradually changes from the west direction to the east direction within the entire 24-hours period (12:00 am UTC August 29, 2005 to 12:00 am UTC August 30, 2005) of the numerical simulations (see Figures 4.145 to 169); in other words, the sloshing motion slowly changes 180° in 24 hours. Therefore, the oscillation (rise and fall of water level) in a semi-enclosed lake induced by a hurricane will be moving around the lake in a counterclockwise-turning pattern whenever a hurricane passes through the regions surrounding the east shore of the lake. While a hurricane circulates counterclockwise and the direction of the accompanying wind generated by the hurricane turns in a counterclockwise pattern, the magnitude of oscillation thoroughly depends on the strength (wind speed) and the duration (length in time) of the wind to a specific direction. In other words, the magnitude of the oscillation (height of rise and fall) associated with the moving direction will be different at each specific location around the lake.

4.6 Risk-Based Design and Analysis

The concept of risk-based design and analysis has been known for many years. The basic concept of risk-based design is schematically shown on Figure 4.170. The risk function accounting for the uncertainties of various factors can be obtained by using the reliability computation procedures. Alternatively, the risk function can account for the potential undesired disaster associated with the failure of hydraulic structures.

Risk costs associated with the failure of hydraulic structure can not be precisely estimated year by year. It is a practical way to quantify it by using an expected cost on the annual basis. The total annual expected cost (TAEC) is the sum of the annual installation cost and annual expected damage cost and TAEC can be mathematically expressed as

$$TAEC = IC * CRF + DC \tag{4.1}$$

where IC is the total installation costs that is determined by the size and configuration of the hydraulic structure; DC is the annual expected damage cost associated with the system failure; and CRF is the capital recovery factor, which leads the present worth of the installation costs to an annual basis, expressed by

$$CRF = \frac{(1+i)^T - 1}{i(1+i)^T} \tag{4.2}$$

with T and i being the expected service life of the system and the interest rate, respectively.

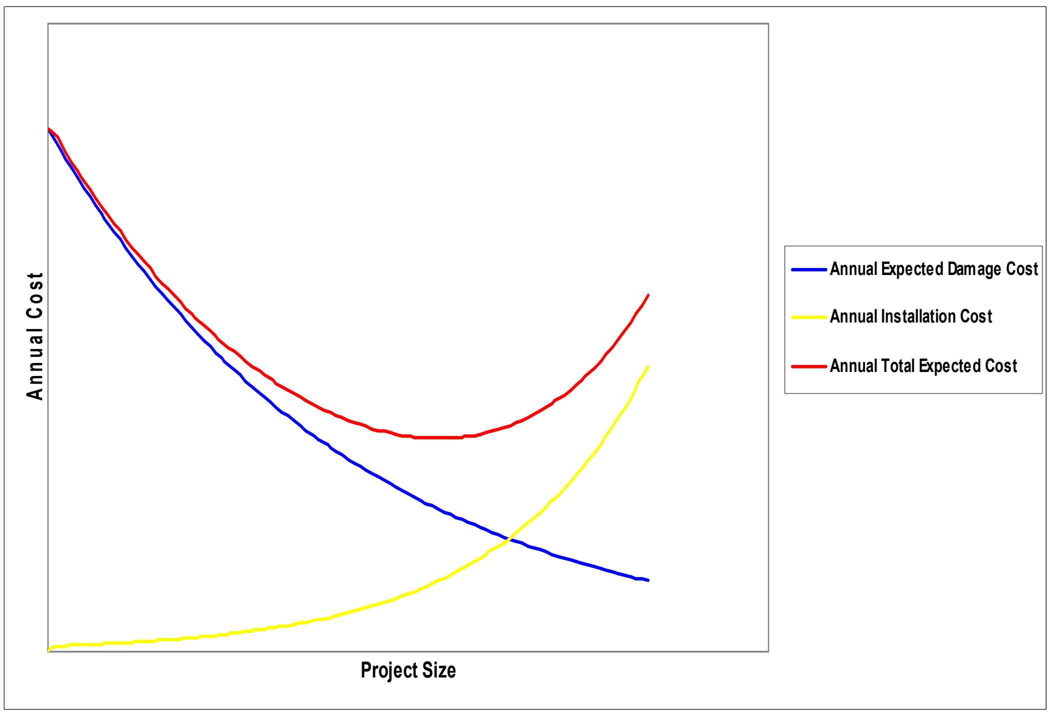

Figure 4.170 Schematic Diagram of Risk-Based Design

As the size of the hydraulic structure increases, the annual installation cost increases while the annual expected damage cost associated with the system failure decreases. The lowest point of the total annual expected cost curve will be used to determine the optimal risk-based design size of the hydraulic structure.

The major application of the present model is to assist the design of the water-front structure surrounding the semi-enclosed water body that has been tremendously influenced by the oscillations induced by hurricanes. Accompanying with the historical records of the paths and strengths of hurricanes which have brought the catastrophic damages to the surrounding communities of the bays, lakes, and harbors, the oscillation phenomena induced by the hurricanes will be fully understood. Therefore, the numerical simulations generated by the present model based on the meteorological inputs can help the planners to determine the optimal size of the hydraulic structures protecting the surrounding communities of the semi-enclosed water body.

Chapter 5: Conclusions

The major objective of this research has been to study the oscillations (storm surges) of the semi-enclosed water body induced by hurricanes. A finite-volume method (FVM) model is developed to solve the depth-averaged, non-linear shallow-water equations (NLSW). The present model is used to investigate the oscillations in Lake Pontchartrain induced by wind generated by the four (4) synthetic hurricanes, including Hurricane Katrina, between 00:00 UTC August 29, 2005 and 00:00 UTC August 30, 2005. The available meteorological data of Hurricane Katrina is used to re-generate the hurricane for the present model and the available measured data of the water levels in Lake Pontchartrain is used to verify the simulated water surface elevations (WSE's) obtained from the present model.

5.1 Summary of Model Verification

The comparison between the measured hydrograph and the predicted hydrograph obtained from the present model at each one of the following eight (8) sites: the 17th Street Canal, the Orleans Avenue Canal, the London Avenue Canal, the IHNC-Lakefront Airport, Midlake, Bayou Labranch, Pass Manchac, and Little Irish Bayou shows:

1. The general trends of the rise and fall of water level are correctly predicted at the 17th Street Canal, the Orleans Avenue Canal, the London Avenue Canal, the

IHNC-Lakefront Airport, and the Midlake sites by the present model when they are compared with the general trends of the rise and fall of water level showing on the available field data at these five (5) sites.

2. The differences of the maximum water surface elevation (WSE) between the predicted hydrographs obtained from the present model and the field observatory hydrographs measured at these four (4) sites along the south shore of Lake Pontchartrain, the 17th Street, the Orleans Avenue and the London Avenue Canals, and the IHNC-Lakefront Airport are within the range of 0.01 to 0.36 meter (or 0.3% ~ 10%).

3. As presented in Figures 4.7 and 4.13, the Bayou La Branche site is not within the general boundary of Lake Pontchartrain. Besides, the Bayou La Branche gage (NOAA Station ID: 8762372) is connected to Lake Pontchartrain by a channel which is about 0.5 mile along. Therefore, the low water surface elevations recorded by the gage are due to the geographic characteristics of the gage location. However, the general trend of the water level is reasonably predicted by the present model when the computed hydrograph is compared with the observed hydrograph; in addition, the difference of the maximum water surface elevation (WSE) between the predicted magnitude made by the present model and the estimated magnitude demonstrated by IPET is within the range of 0.5 to 0.6 meter (or 20% ~ 25%) at the Bayou La Branche site.

4. As presented in Figures 4.7 and 4.13, the Pass Manchac site is located outside the general boundary of Lake Pontchartrain. Thus, the current computations do not

accommodate the geographic and hydraulic complexities among the Pass Manchac area. However, the general trend of the water level is reasonably predicted by the present model when the computed hydrograph is compared with the observed hydrograph at the Pass Manchac site.

5. The storm surges intruding from Gulf of Mexico through the swamps along Lake Pontchartrain are not included in the present model. According to the IPET report, the majority of the swamps along the east shore of Lake Pontchartrain has been inundated by the storm surges from Gulf of Mexico before the start of the numerical simulations (12:00 am August 29, 2005). Hence, the water surface elevation (WSE) at Gulf of Mexico via Lake Borgne and Lake St. Catherine can significantly affect the rise and fall of the water level at the east part of Lake Pontchartrain. However, the present model still reasonably predicts the general trend of the rise and fall of the water level when the computed hydrograph is compared with the observed hydrograph at Little Irish Bayou site.

Based on these five (5) observed results, the present model has been verified to be a reliable tool to study the oscillations of semi-enclosed water body induced by hurricanes. Both the predicted hydrographs and the predicted hourly contour maps showing the water surface elevation (WSE) of Lake Pontchartrain obtained from the present model provide valuable information in studying the oscillations of a semi-enclosed lake induced by hurricanes.

5.2 Major Findings from Applications of the Present Model to Synthetic Hurricanes

The major conclusions drawn from the hydrographs and the hourly contour maps showing the oscillations of Lake Pontchartrain induced by the winds generated by the four (4) synthetic hurricanes and the accompanying meteorological characteristics of these four (4) hurricanes are summarized in the following sub-sections.

5.2.1 Synthetic Hurricane No. 1

The first synthetic hurricane assumes Hurrcane Katrina tracking on its original route. All meteorological parameters of this synthetic hurricane are identical to Hurricane Katrina, including the forward moving track. This synthetic hurricane moves in a nearly north direction and passes through the regions close to the east shore of Lake Pontchartrain between 12:00 am and 06:00 pm UTC August 29, 2005 corresponding to the first 18-hours of the numerical simulations made by the present model. Because of these two characteristics of the interaction between the hurricane and the lake, the sloshing motion of the lake water surface rotates in a counterclockwise pattern as the hurricane circulates counterclockwise. The closest encounter between Hurricane Katrina and Lake Pontchartrain takes place between 12:00 and 06:00 pm UTC (or 7:00 am and 1:00 pm Local Time) August 29, 2005. During this 6-hours period, the highest amplitude of oscillation (maximum WSE) along the south shore of the lake happens around 03:00 pm UTC (10:00 am Local Time) with a magnitude of 3.27 m to 3.30 m predicted by the present model while the highest water level, reported in IPET report, associated with the time is within the range of 10.8 ft to 12.0 ft (or 3.29 m to 3.66 m) along the south shore of Lake Pontchartrain. Based on the IPET report, the majority of floods caused by the storm surge induced by Hurricane Katrina in the highly-populated communities along the south shore of Lake Pontchartrain took place within this 6-hours period. Consequently, these floods created the severe human loss and property damages in these communities.

The moving direction of the storm surge changes from the west direction to the east direction during the first 16-hours period of the numerical simulations (the sloshing motion changes 180° in 16 hours). Therefore, the oscillation (rise and fall of water level) in a semi-enclosed lake induced by a hurricane will be moving around the lake in a counterclockwise-turning pattern. Meanwhile, the magnitude of the oscillation (height of rise and fall) associated with the moving direction will be different at each specific location around the lake.

Since the major communities, i.e. New Orleans, of business importance, dense population and historical heritage, are located within the region along the south shore of Lake Pontchartrain, a natural disaster of a catastrophic scale will have impact of national significance. When the eye of Hurricane Katrina is passing through the region along the east shore of Lake Pontchartrain, the highest amplitude (maximum WSE) of oscillation along the south shore of Lake Pontchartrain takes place at the time at which the sloshing motion in the lake is moving toward the south, directly intruding into the region along the south shore of the lake. Consequently, the major floods caused by these large oscillations induced by Hurricane Katrina within a short period of time along the south shore of Lake Pontchartrain create a catastrophe with enormous impacts to the city of New Orleans even though the city is protected by the hurricane protection systems built under the Lake Pontchartrain and Vicinity project (one of the three major projects under a comprehensive hurricane protection plan for New Orleans and the Southeast Louisiana region).

5.2.2 Synthetic Hurricane No. 2

The second synthetic hurricane assumes Hurrcane Katrina tracking 36 km west of its original route. All other meteorological components of this synthetic hurricane are identical to Hurricane Katrina, except the forward moving track. This synthetic hurricane moves in a nearly north direction and passes through the east part of New Orleans, Louisiana and both the east and central parts of Lake Pontchartrain between 12:00 am and 06:00 pm UTC August 29, 2005 corresponding to the first 18-hours of the numerical simulations made by the present model. Due to these two characteristics of the interaction between the hurricane and the lake, the sloshing motion at Lake Pontchartrain rotates in a counterclockwise pattern as the hurricane circulates counterclockwise. The closest encounter between this synthetic hurricane and Lake Pontchartrain takes place between 12:00 and 06:00 pm UTC August 29, 2005. During this 6-hours period, the highest amplitude of oscillation (maximum WSE) along the south shore of Lake Pontchartrain will occur around 03:00 pm UTC with a magnitude of 3.53 m to 3.86 m as predicted by the present model.

The moving direction of the storm surge changes from the west direction to the east direction during the first 16-hours of the numerical simulations (the sloshing motion changes 180° in 16 hours). Therefore, the oscillation (rise and fall of water level) in a semi-enclosed lake induced by a hurricane will be moving around the lake in a counterclockwise-turning pattern. Meanwhile, the magnitude of the oscillation (height of rise and fall) associated with the moving direction will be different at each specific location around the lake.

5.2.3 Synthetic Hurricane No. 3

The third synthetic hurricane assumes Hurrcane Katrina tracking 72 km west of its original route. All other meteorological parameters of this synthetic hurricane are identical to Hurricane Katrina, except the forward moving track. This synthetic hurricane moves in a nearly north direction and passes over the west shore and its surrounding regions of Lake Pontchartrain between 12:00 am and 06:00 pm UTC August 29, 2005 corresponding to the first 18-hours of the numerical simulations made by the present model. Due to these two characteristics of the interaction between the hurricane and the lake, the sloshing motion at Lake Pontchartrain rotates in a clockwise pattern even though the hurricane circulates counterclockwise. The closest encounter between this synthetic hurricane and Lake Pontchartrain takes place between 12:00 and 06:00 pm UTC August 29, 2005. During this 6-hours period, both the lowest and the highest amplitudes of oscillation (or minimum and maximum WSE's) along the south shore of Lake Pontchartrain will occur around 03:00 pm UTC with the highest magnitude of 3.11 m to 3.33 m as predicted by the present model.

The moving direction of the storm surge changes from the west direction to the east direction during the first 16-hours of the numerical simulations (the sloshing motion changes 180° in 16 hours). Therefore, the oscillation (rise and fall of water level) in a semi-enclosed lake induced by a hurricane can be moving around the lake in a clockwise-turning pattern whenever a hurricane passes through regions surrounding the west shore of the lake. Meanwhile, the magnitude of the oscillation (height of rise and fall) associated with the moving direction will be different at each specific location around the lake.

5.2.4 Synthetic Hurricane No. 4

The fourth synthetic hurricane assumes Hurrcane Katrina tracking on its original route but with reduced forward speeds; hence, two major meteorological parameters of this synthetic hurricane, central pressures and radii of maximum winds, are obtained by modifying the observatory data of Hurricane Katrina. This synthetic hurricane moves in a nearly north direction and passes through the regions nearby the east shore of Lake Pontchartrain between 12:00 am UTC August 29, 2005 and 12:00 am UTC August 30, 2005 corresponding to the entire 24-hours of the numerical simulations made by the present model. Because of these two characteristics of the interaction between the hurricane and the lake, the sloshing motion at Lake Pontchartrain rotates in a counterclockwise pattern as the hurricane circulates counterclockwise. The closest encounter between this synthetic hurricane and Lake Pontchartrain takes place between 03:00 pm UTC August 29, 2005 and 12:00 am UTC August 30, 2005. During this 9-hours period, the highest amplitude of oscillation (maximum WSE) along the south shore of Lake Pontchartrain will happen around 06:00 pm UTC with a magnitude of 4.33 m to 4.45 m predicted by the present model. Evidently, the maximum water surface elevations (WSE's) along the south shore of Lake Pontchartrain induced the wind generated by this synthetic hurricane (Hurricane Katrina tracking on its original route with reduced forward speeds) will be 1 m higher than the ones induced by the wind generated by the genuine Hurricane Katrina. Thus, should this condition occur, the floods and the accompanying catastrophes caused by this synthetic hurricane would be much severe than the ones caused by Hurricane Katrina.

The moving direction of the storm surge changes from the west direction to the east direction during the entire 24-hours of the numerical simulations (the sloshing motion slowly changes 180° in 24 hours). Therefore, the oscillation (rise and fall of water level) in a semi-enclosed lake induced by a hurricane would still be moving around the lake in a counterclockwise-turning pattern if the hurricane would pass over the regions nearby or surrounding the east shore of the lake. Meanwhile, the magnitude of the oscillation (height of rise and fall) associated with the moving direction will be different at each specific location around the lake.

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