Archives of Hydro-Engineering and Environmental Mechanics
Vol. 51 (2004), No. 1, pp. 75–84

Modelling Freshwater Inflows in a Shallow Lake

J. Alex McCorquodale*, **Ioannis Georgiou****

* Dept. of Civil and Environmental Engineering, University of New Orleans,
817 Engineering Bldg., New Orleans, LA 70148, e-mail: jmccorqu@uno.edu
** Dept. of Geology and Geophysics, University of New Orleans, LA 70148,
e-mail: igeorgiou@uno.edu

(Received March 20, 2003; revised September 16, 2003)

Abstract

A three-dimensional primitive equation hydrodynamic model was used to investigate the impacts from freshwater introduction into a shallow brackish lake. The proposed effort is an attempt to reduce seasonal salinity intrusion from the Gulf of Mexico through tidal passes and navigation canals during periods of low tributary flows. The model is a modification of the Princeton Ocean Model.

Key words: modeling, hydrodynamics, salinity, intrusion, diversion

1. Introduction

Lake Pontchartrain is a brackish estuarine lake in Southeastern Louisiana with a mean depth of 3.8 m (0.5 m to 5 m) and an area of approximately 1630 km^2 (Fig. 1). The east end of the lake has a diurnal tide with ranges from 3 to 45 cm. Because it is very shallow, the Lake water column is generally well mixed. The Lake has two main natural tidal passes, Rigolets and Chef Menteur, and a third, man-made tidal pass, the Inner Harbor Navigation Canal (IHNC), that connect to the Gulf of Mexico through Lake Borgne. In the west, the Lake is connected to Lake Maurepas by Pass Manchac. The Lake receives runoff from several rural drainage basins, and an urban watershed to the south of the Lake, which includes the City of New Orleans. There are periodic diversions from the Mississippi River with a return period of about 7 years. Salt fluxes in the estuary are mainly through the IHNC and the Rigolets. Saltwater intrusion from the IHNC causes periodic but strong stratification impacting up to 250 km^2 of the Lake bottom near the (Poirrier 1978, Haralampides et al. 2000, Georgiou et al. 2000). Circulation currents in the Lake are wind driven except near the tidal passes.

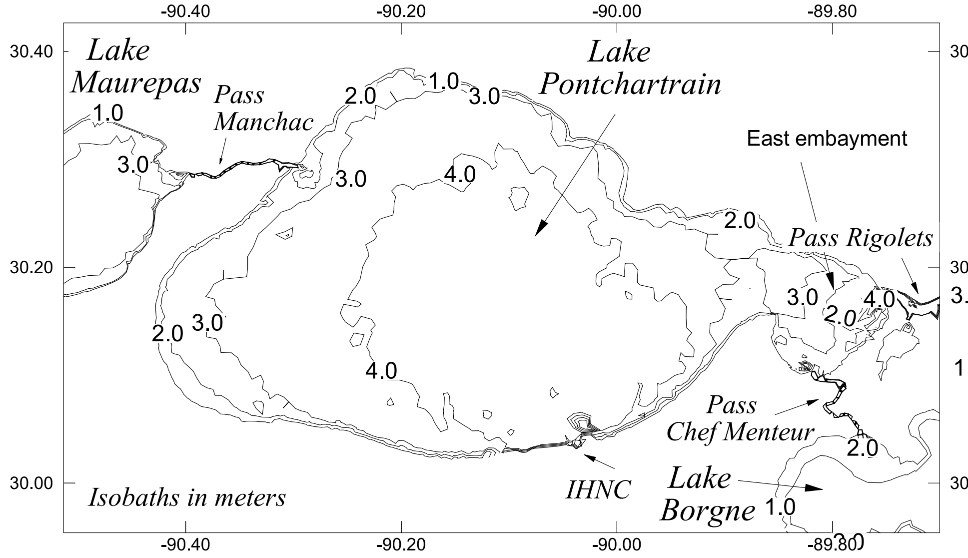

Fig. 1. Geographic and bathymetric features of the Lake Pontchartrain estuary

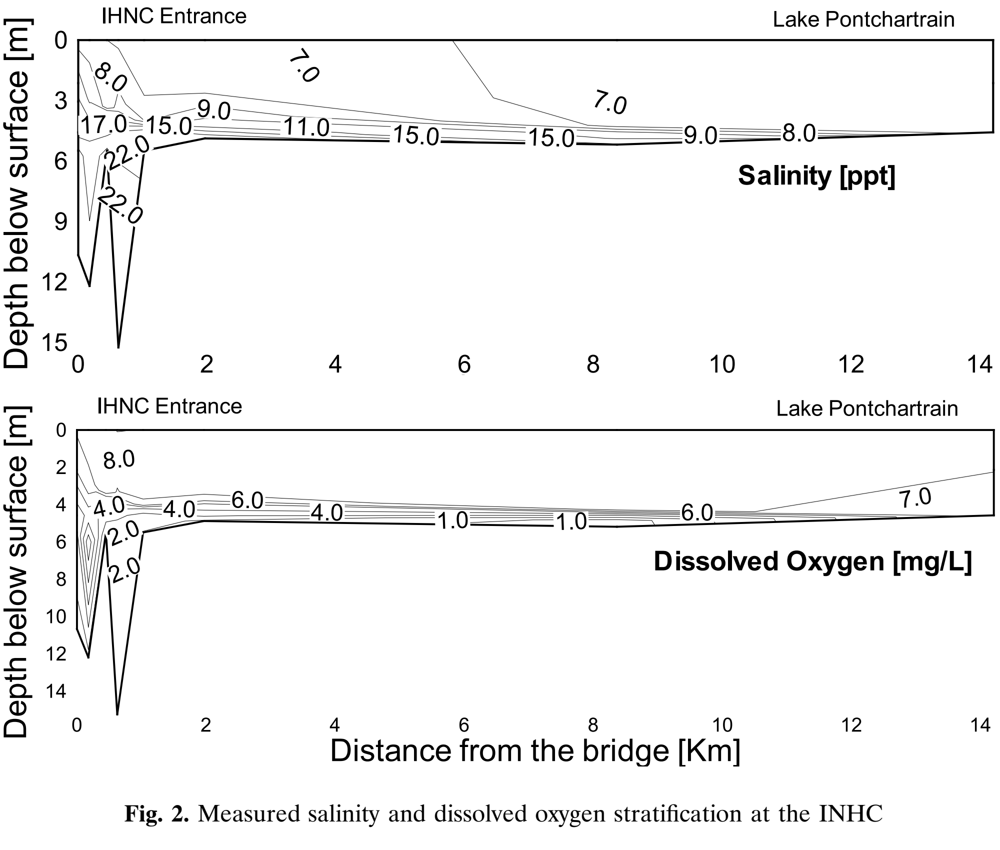

Fig. 2. Measured salinity and dissolved oxygen stratification at the INHC

2. Background

Poirrier (1978) demonstrated salinity and dissolved oxygen (DO) stratification near the IHNC using field data. Haralampides et al. (2000) and Georgiou et al. (2000) verified salinity and DO stratification in the lake, and further demonstrated through vertical profiles in the water column that the process is dynamic. Vertical profiles of recording temperature, salinity and DO were collected at 12 stations near the IHNC at weekly intervals. More samples were collected near the bed in order to define the salt wedge interface. The profiles showed that high salinity gradients in combination with high temperatures and high Sediment Oxygen Demand (SOD) during the summer months, resulted in extremely low DO values near the bed, indicating that less mixing occurs under these conditions. Time series data from all stations showed a strong correlation between salt gradients, near bed temperatures and bottom DO. On the other hand, occasional strong salt gradients during the winter months did not produce a similar effect primarily due to low temperatures and higher storm related wind activity.

3. Model Description

In order to further study density currents in the lake, and to determine under what conditions saltwater intrusion is a numerical tool is essential. For this study, the Princeton Ocean Model (Blumberg and Mellor 1987) was configured for the study in Lake Pontchartrain. The model contains a free surface, a 2.5 level turbulence closure scheme for vertical mixing representation (Mellor and Yamada 1982), nonlinear advective terms, coupled density and velocity fields and heating and cooling. Other model features include orthogonal curvilinear coordinates in the horizontal and sigma coordinates in the vertical, allowing for surface and bottom refinement. Initial model configuration includes a domain of 115 × 70 equal in size (600 m) horizontal grid cells and 20 sigma layers with surface and bottom logarithmic refinement. The final grid resolution of the model contains a horizontal domain of 169 × 70 nodes with cells varying in size from 150 m to 950 m and similar vertical resolution.

The model was driven with a diurnal tide (23 hour period, 17 cm amplitude) at the Rigolets, Chef Menteur and the IHNC, and wind stress. The wind stress applied was constant throughout the domain for each simulation and speeds of 2.5, 5, and 7.5 m/s were used. The model was also run without wind as a basis of comparison. The lateral boundary conditions included constant temperature and salinity for tributary flows and linear thermal and salt stratification at the tidal inlets. A constant feed of higher density gradients was used simulating a salt wedge. Surface forcing for temperature and salinity were not included during initial runs. The specific simulations reported in this paper have ambient salinities of 10–13 ppt, which represent values during the 1999 summer drought period.

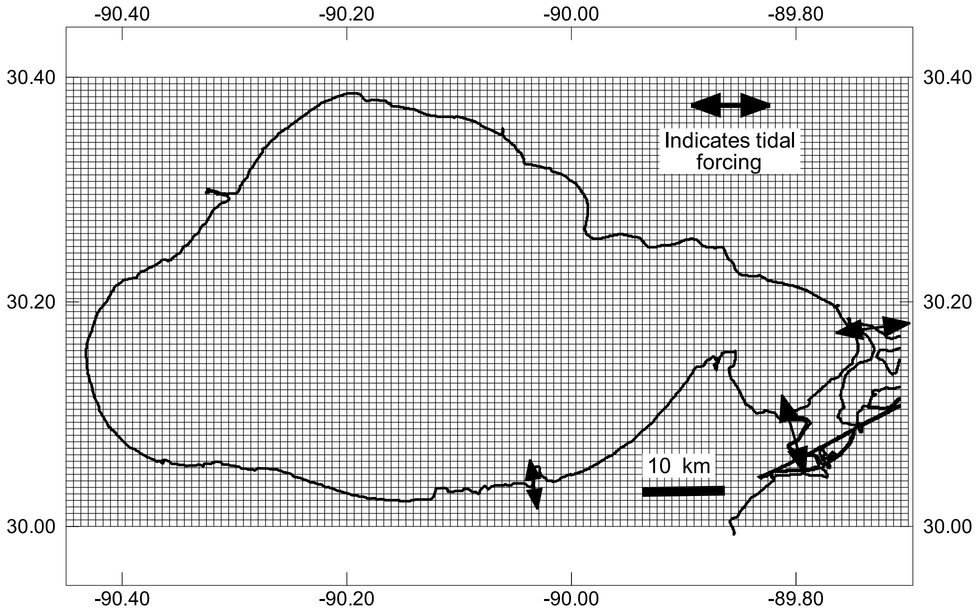

Fig. 3. Model computational domain for Lakes Pontchartrain and Maurepas

Recent experiments using a domain which includes the complete estuary extending to the Gulf of Mexico utilizes similar varying resolution of 250 to 950 m (Fig. 4) but dynamic and more realistic boundary conditions. This model setup uses time dependent tributary flows, wind, tides, and freshwater inflow hydrographs.

Both models were calibrated for elevation using hourly water level observations from five stations in the lake, and for velocity, using GPS equipped drifter deployments. Calibration for transport was performed using satellite imagery, and field data collected by Haralampides (2000) and Georgiou (2002).

4. Results and Discussion

The average wind speed over Lake Pontchartrain is generally above 3.0 m s^{-1}, thus dominating the circulation forcing. The model predicted a typical depth averaged flow pattern over the domain consisting of two gyres rotating in the opposite directions. Flow was downwind near the surface and in the shallow regions of the Lake (shoreline) and upwind in the deeper central regions (Fig. 5). Although depth-averaged currents exhibited the double gyre pattern, velocity variations in the vertical were non-uniform. In fact, higher velocity magnitudes were observed near the bed in the deeper region of the Lake than in the shallow parts; this results in a near bed gyre in the western shallower part of the Lake with similar rotation

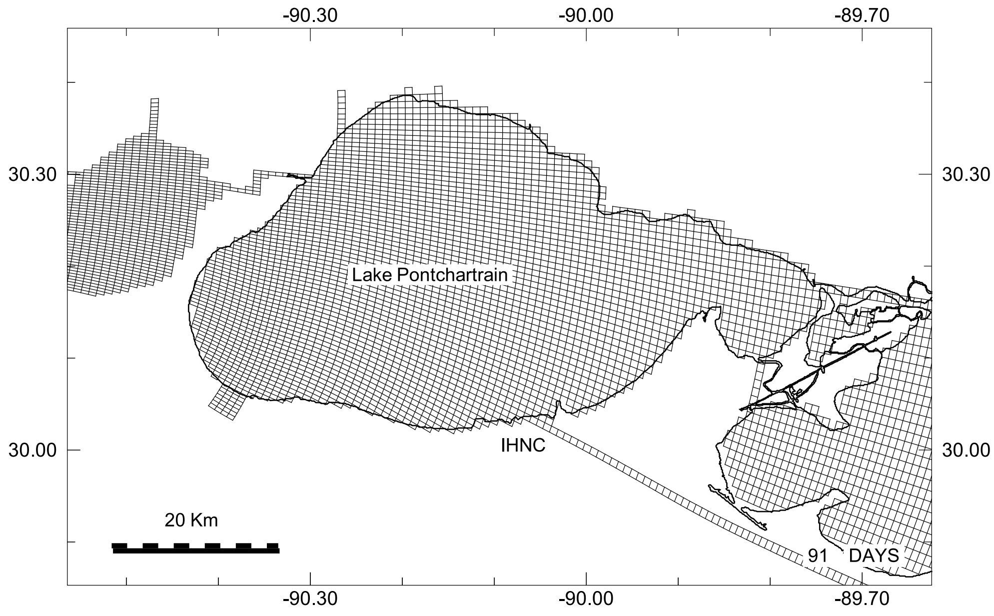

Fig. 4. Model computational domain of the Estuary

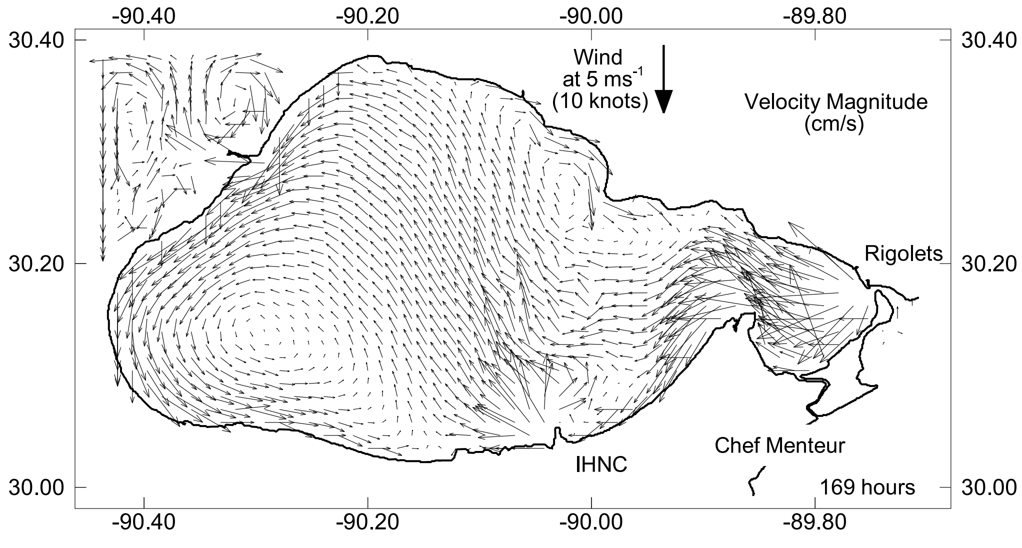

Fig. 5. Typical wind driven circulation pattern in Lake Pontchartrain. (Currents are depth-averaged; wind speed 5 m/s from the north)

to the depth-averaged gyre, only with a centre shifted to the west. This pattern was consistent for winds with northerly and southerly components. Similarly, easterly and westerly wind forcing produced a gyre in the shallow north end of the Lake. The circulation patterns in Lake Maurepas were similar to those predicted in Lake Pontchartrain for each wind direction.

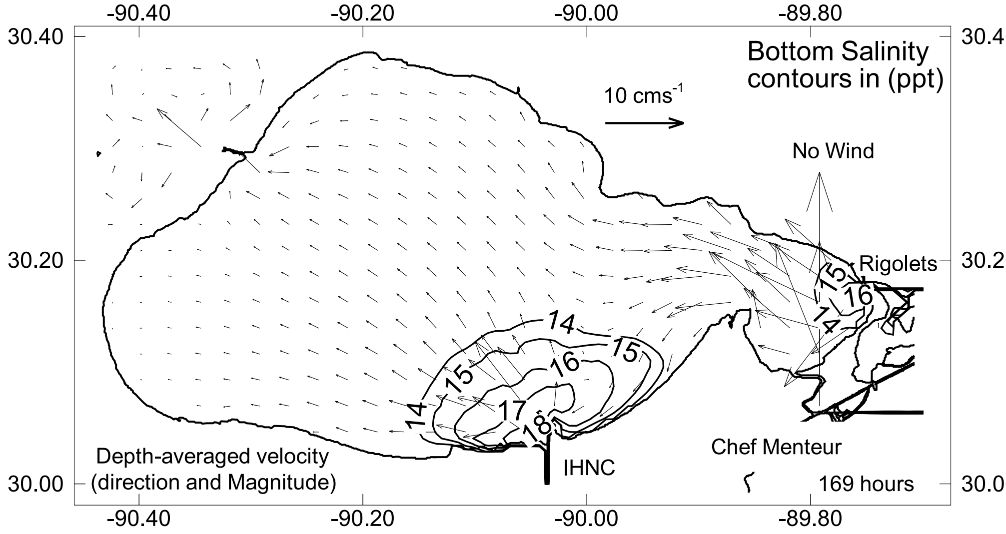

Fig. 6. Tidal depth-averaged currents and bottom salinity

The return flow near the bed has a great effect on the intruding salinity wedge. In terms of stratification, the model produced similar results to the field data regarding the impact area and plume expansion. The ‘no wind’ simulation indicated a radial expansion of the saltwater plume near the IHNC expanding and contracting in relation to the tidal cycle with decreasing rate of advance with each flood cycle until equilibrium was reached in approximately 7 days (Fig. 6). Similar density effects were observed at the Rigolets, but there was greater vertical mixing and impacted area was limited to the east embayment. Simulations with wind stress produced a shift on the position of the saltwater plume that depended on the direction and magnitude of the wind. The spreading of the saltwater wedge is in general in the direction of the near bed current, typically with an upwind direction. Northerly and westerly winds favor the plume expansion to the north and west respectively. For strong northerly winds, periodic mixing was observed near the source during the ebb cycle, at times, disconnecting the density current from its source. On the other hand, southerly winds helped suppress the northerly expansion of the plume but assisted in the lateral expansion along the south shore to the east and west. At high and sustained southerly winds around 7.5 m/s upwelling was observed near the south end of the Lake. Figure 7 demonstrates an expansion and shift of the intruding wedge under sustained northerly winds at 5 m/s. The model predicted a thickness of the density current in the order of 1.5 m or greater near the IHNC, and 0.7–0.9 m near the advancing front of the plume (Fig. 8). Field data indicated that the thicknesses rarely reached these values, often ranging from 1–2 m and 0.3–0.6 m respectively. However, the predicted area and extent of the salt water intrusion as shown in Figures 7 and 8 is very similar to the field measured plume as indicated in Figure 2.

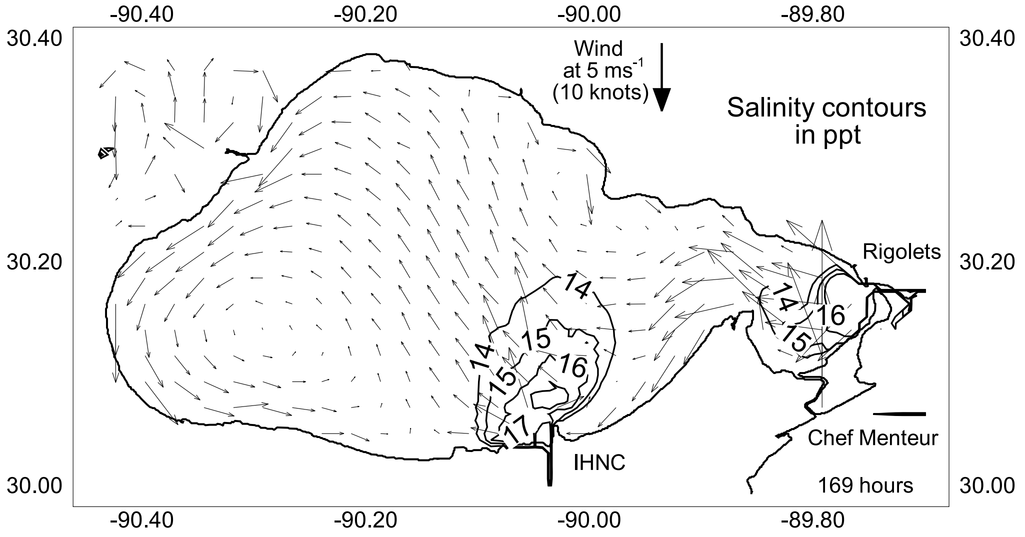

Fig. 7. Wind-driven depth-averaged currents and bottom salinity

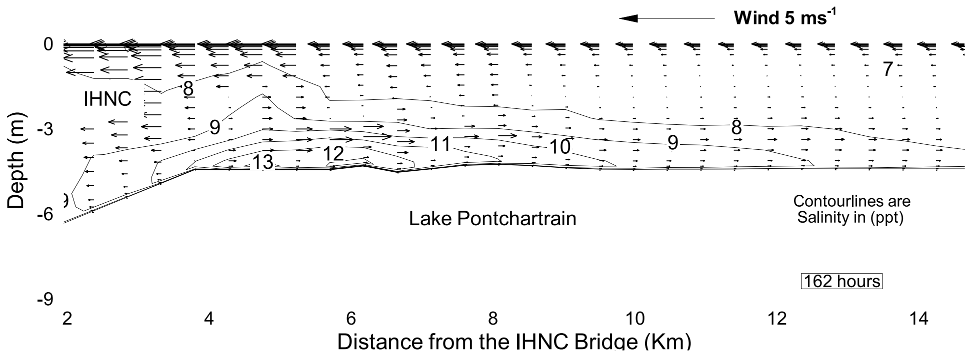

Fig. 8. Computed salinity stratification near the IHNC

5. Applications

The model was used to investigate impacts from proposed management scenarios not only for reduction of salinity intrusion, but related impacts from diversions of Mississippi River water through neighboring marshes and canals in the western part of the study area. This area, to the west of the basin and west of Lake Maurepas is rich in cypress trees, which do not tolerate highly saline waters. In fact, growth and reproduction is halted at 4 ppt and mortality begins around 6 ppt. Lake Maurepas generally contains fresh water. In the summer of 1999, following a drought in the area, salinities above 4 ppt were recorded.

A diversion of 285 m^3/s into the western portion of Lake Pontchartrain at the Bonnet Carré Spillway is proposed; this would take place in the spring when elevation in the Mississippi River is high. The model forcing was prepared for the proposed period using wind and tidal information from previous years. The model was run for a 90-day period with a gradual increase of the diversion flow to the maximum value over a period of 1 day. The volume of Lake Pontchartrain is approximately 7×10^9 m. The proposed flow has a theoretical detention time of 9 months.

Figure 9 shows the isohalines for the initial condition and at 30, 60 and 90 days after the start of the diversion. The model indicated that the initial arrival time at the east end of the Lake was very rapid at less than 10% of the theoretical detention time. Between 60 and 90 days the rate of advancement of the 1 and 2 ppt isohalines slows down significantly. This is in part due to the diffusion of higher salinity water from Lake Borgne into Lake Pontchartrain via the Passes. The double gyre system in Lake Pontchartrain appears to separate the Lake into two cells that are partially mixed by wind shear. This assists in the diffusion of saline waters from the east and contributes to the stabilization of the isohalines in the mid-lake region in approximately 25% of the theoretical detention time for the proposed diversion flow. A possible negative affect of this diversion may be an algal bloom in the western portion of Lake Pontchartrain where the high nutrient Mississippi River water has a long residence time.

6. Conclusions

The POM simulations confirmed previous studies that showed formation of a typical two-gyre circulation pattern due wind shear. In addition, the gyre on the western rim of the Lake Pontchartrain oscillated with the tidal cycle. This was observed for winds from the north and south and served as a transport and dispersion mechanism for the western part of the lake. Water circulation in Lake Pontchartrain due to tidal exchanges and wind are significant for the expansion and deformation of the saltwater plume from the IHNC. Model results show a significant interaction of density currents and bottom currents. In general, a north wind caused an added expansion of the plume in the northerly direction while a

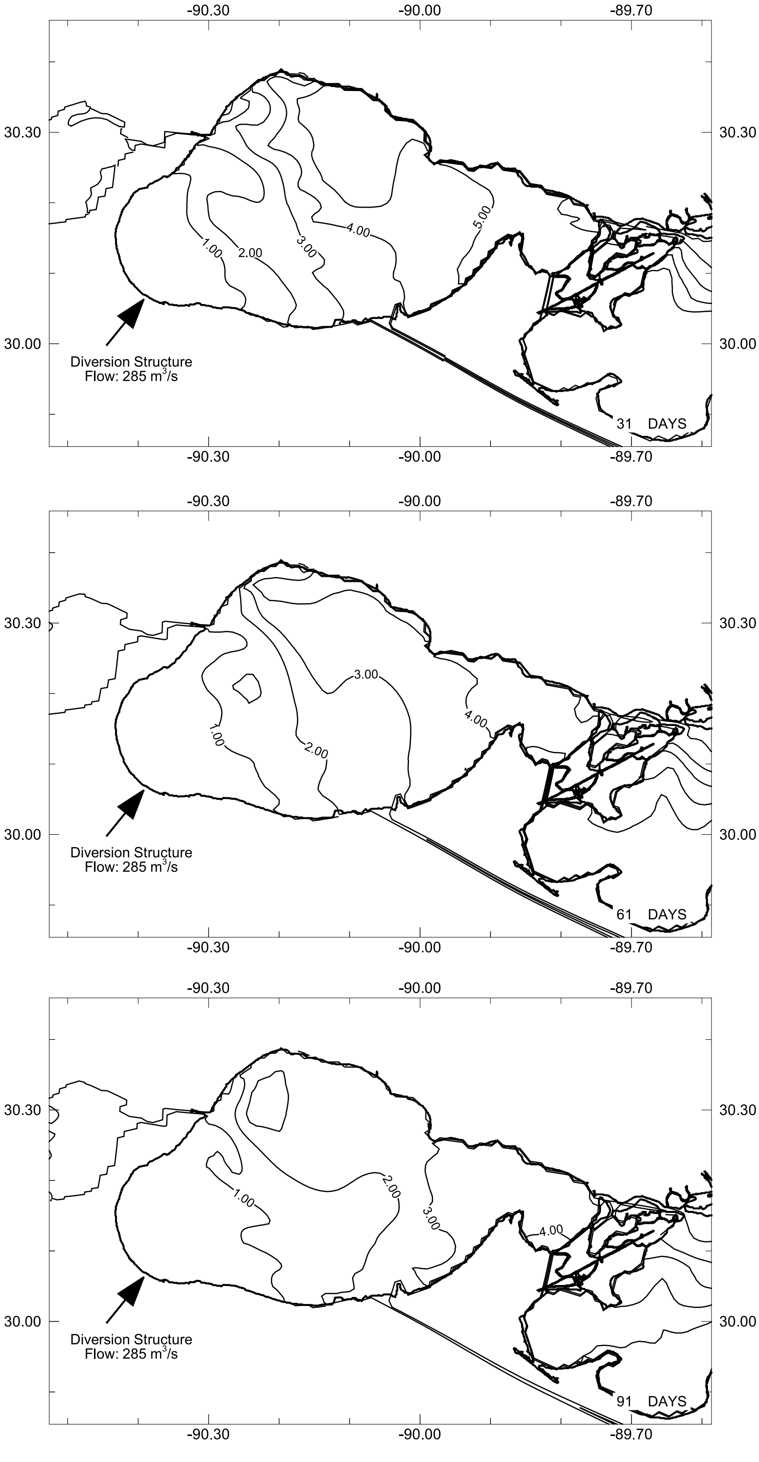

Fig. 9. Surface salinity from a diverted flow of 285 m^3/s from the Mississippi River during the spring at time = 30 days (top), 60 days (middle) and 90 days (bottom)

southerly wind suppressed the northerly advance of the plume. Bottom currents in the lake, which tend to be counter to the wind, exert a shear on the plume thus causing it to shift upwind. Similar shifts were noted for all wind directions but easterly and southeasterly winds generate sufficient long-shore currents to keep the density current suppressed throughout the 7 day run period.

Finally, POM predicted that relatively small diversions (flows with detention times of the order 9 months) from the Mississippi River into Lake Pontchartrain would result in a relatively stable and acceptable salinity gradient from west to east in Lake Pontchartrain in approximately 25% of the detention time. This diversion also suppressed the salt water intrusion at the IHNC.

References

Blumberg A. F. and Mellor G. L. (1987), A Description of a Three-Dimensional Coastal Nodel, *Coastal and Estuarine Sciences*, Vol. 4, 1–16, American Geophysical Union, Washington, DC.

Georgiou I., McCorquodale J.A. (2000), Salinity Stratification from a Navigation Canal in a Shallow Lake, [in:] *Stratified Flows*, Laurence G. A., Pieters R. and Yonemitsu N., Eds., University of British Columbia, Vancouver, Canada, Vol. 2, 859–864.

Georgiou I. (2002), *Three-Dimensional Hydrodynamic Modeling of Salinity Intrusion and Circulation in Lake Pontchartrain*, Ph.D. Dissertation, Dept. of Civil and Environmental Engineering, University of New Orleans, New Orleans, LA.

Haralampides K. (2000), *A Study of the Hydrodynamics and Salinity Regimes of the Lake Pontchartrain System*, Ph.D. Dissertation, Dept. of Civil and Environmental Engineering, University of New Orleans, New Orleans, LA.

Haralampides K., Georgiou I. and McCorquodale J. A. (2000), Water Quality Impacts on the Lake Pontchartrain Estuarine System, *Proceedings from the 75th Annual Conference of the Water Environment Federation*, October 15–21, Anaheim, California.

Mellor G. and Yamada T. (1982), Development of a Turbulence Closure Model for Geophysical Fluid Problems, *Rev. Geophys. Space Phys.*, 20, 851–875.

Poirrier M. A. (1978), Studies of Salinity Stratification in Southern Lake Pontchartrain near the Inner Harbor Navigation Canal, *Proceedings of the Louisiana Academy of Sciences*, Vol. 151, 26–35.