Environmental Impact of Flow, Sediment and Salinity on Ecosystem of Lake Pontchartrain due to flood release from Bonnet Carré Spillway

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Abstract: In order to protect the city of New Orleans from the Mississippi River flooding, the Bonnet Carré Spillway (BCS) was constructed from 1929 to 1936 to divert flood water from the river into Lake Pontchartrain and then into the Gulf of Mexico. However, a BCS opening event may cause many environmental problems in the lake. To evaluate the environmental impacts of the flood water on lake ecosystems, it is important to understand the hydrodynamics as well as pollutant transport in the lake. Lake Pontchartrain is a large shallow lake and the water column is well mixed. During a flood release event, the flow discharge over the spillway produces significant effects on the lake hydrodynamics. The water movements within the lake were also affected by wind and tide. In this study, a two- dimensional depth-averaged numerical model was applied for simulating the flow circulations, salinity and sediment distributions in Lake Pontchartrain during the 1997 flood. The simulated results were compared with satellite imagery and field measured data provided by the United States Geological Survey (USGS) and the United States Army Corp of Engineers (USACE). The environmental impacts of flow, sediment and salinity on ecosystem of Lake Pontchartrain due to flood release from BCS in 1997 were studied, and the reasons for algal bloom occurrences and fish habitat changes were analyzed.

Keywords: Numerical model, Sediment transport, Salinity, Satellite imagery, Environmental impact, Algal bloom

Introduction

Lake Pontchartrain is a brackish estuary located in southeastern Louisiana, United States. It is the second-largest saltwater lake in U.S. The lake covers an area of 1630 square km with a mean depth of 4.0 meters. It is an oval-shaped quasi-enclosed water body with the main east-west axis spanning 66 km, while the shorter north–south axis is about 40 km.

Lake Pontchartrain has served the surrounding communities for more than two centuries. The coastal zone of the lake and its basin has offered opportunities for fishing, swimming, boating, crabbing and other recreational activities. This Lake Basin is Louisiana's premier urban estuary and nearly one-third of the state population lives within this area.

The Lake is also used as a flood release area for protecting the city of New Orleans. When the water surface level in the Mississippi River in New Orleans approaches the flood stage of 5.18m, Bonnet Carré Spillway (BCS) will be opened to divert water from the river into Lake Pontchartrain and then into the Gulf of Mexico. These flood release events may change the distributions of salinity, nutrients and suspended sediment in the lake, and as a result, cause a lot of environmental problems in the lake.

To evaluate the environmental impacts of a flood release event from BCS on lake ecosystems, it is important to understand the hydrodynamics as well as sediment transport and salinity distribution in the lake. Lake Pontchartrain is a large shallow lake and the water column is well mixed. In general, the water movements within the lake are primarily wind- and tide-induced. However, during a flood releasing, the flow discharge over the spillway produces significant effects on the lake hydrodynamics. In this study, a two- dimensional depth-averaged numerical model, CCHE2D, was applied for simulating the flow circulations, salinity and sediment distributions in Lake Pontchartrain during the 1997 flood release. The simulated results were compared with satellite imagery and field measured data provided by USGS and USACE.

Model Descriptions

To simulate the flow field, sediment transport, and salinity distribution in Lake Pontchartrain during a flood release event, a two- dimensional depth-averaged model, CCHE2D, was applied. CCHE2D is a 2D hydrodynamic model that can be used to simulate unsteady turbulent flows with irregular boundaries and free surfaces (Jia et al., 1999, 2002). It is a finite element model utilizing a special method based on the collocation approach called the “efficient element method”. This model is based on the 2D Reynolds-averaged Navier-Stokes equations. By applying the Boussinesq approximation, the turbulent stress can be simulated by the turbulent viscosity and time-averaged velocity. There are several turbulence closure schemes available within CCHE2D, including the parabolic eddy viscosity, mixing length, k–ε and nonlinear k–ε models.

Governing equations

The free surface elevation of the flow is calculated by the continuity equation:

$$\frac{\partial h}{\partial t}+\frac{\partial uh}{\partial x}+\frac{\partial vh}{\partial y}=0 \tag{1}$$

The momentum equations for the depth-integrated two-dimensional model in the Cartesian coordinate system are:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial \eta}{\partial x}+\frac{1}{h}\left(\frac{\partial h\tau_{xx}}{\partial x}+\frac{\partial h\tau_{xy}}{\partial y}\right)+\frac{\tau_{sx}-\tau_{bx}}{\rho h}+f_{Cor}v \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial \eta}{\partial x}+\frac{1}{h}\left(\frac{\partial h\tau_{yx}}{\partial x}+\frac{\partial h\tau_{yy}}{\partial y}\right)+\frac{\tau_{sy}-\tau_{by}}{\rho h}-f_{Cor}u \tag{3}$$

where u and v are the depth-integrated velocity components in x and y directions, respectively; t is the time; g is the gravitational acceleration; η is the water surface elevation; ρ is the density of water; h is the local water depth; f_{Cor} is the Coriolis parameter; τ_{xx}, τ_{xy}, τ_{yx} and τ_{yy} are depth integrated Reynolds stresses; and τ_{sx} and τ_{sy} are surface share stresses in x and y directions, respectively; and τ_{bx} and τ_{by} are shear stresses on the bed and flow interface in x and y directions, respectively.

The turbulence Reynolds stresses in equations (2) and (3) are approximated according to the Bousinesq’s assumption that they are related to the main rate of the strains of the depth-averaged flow field and an eddy viscosity coefficient ν_t which is computed using the Smagorinsky scheme:

$$\nu_t=\alpha\Delta x\Delta y\left[\left(\frac{\partial u}{\partial x}\right)^2+\frac{1}{2}\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2\right]^{1/2} \tag{4}$$

The parameter α ranges from 0.01 to 0.5. In this study, it was taken as 0.1.

The suspended sediment transport equation can be written as

$$\frac{\partial c}{\partial t}+u\frac{\partial c}{\partial x}+v\frac{\partial c}{\partial y}=\frac{\partial}{\partial x}\left(D_{cx}\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_{cy}\frac{\partial c}{\partial y}\right)+S_c \tag{5}$$

in which c is the sediment concentration; D_{cx} and D_{cy} are the mixing coefficients of suspended sediment in x and y directions, respectively; S_c is the source term, which represents the local balance of suspension and deposition:

$$S_c = -\frac{1}{h}(\omega_s c_a - \omega_s c_{a,e}) \tag{6}$$

where c_a is the sediment concentration near the bed surface with a reference height of a; ω_s is the fall velocity; $c_{a,e}$ is the depth-averaged sediment concentration under an equilibrium condition.

The salinity transport equation can be written as

$$\frac{\partial S}{\partial t} + u\frac{\partial S}{\partial x} + v\frac{\partial S}{\partial y} = \frac{\partial}{\partial x}\left(D_{sx}\frac{\partial S}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_{sy}\frac{\partial S}{\partial y}\right) \tag{7}$$

in which S is the salinity; D_{sx} and D_{sy} are the mixing coefficients of salinity in x and y directions, respectively.

Numerical solution

In the numerical model, the unsteady equations are solved using the time-marching scheme. The velocity correction method is applied to solve dynamic pressure and enforce mass conservation. Provisional velocities are solved first without the pressure term, and the final solution of the velocity is obtained by correcting the provisional velocities with the pressure solution (Jia et al., 2002). The system of the algebraic equations is solved using the Strongly Implicit Procedure (SIP). Sediment concentration and salinity can be obtained by solving Eqs. (5) and (7) numerically.

Model Application

Study area

Lake Pontchartrain is a large shallow lake with an area of 1630 km^2 and a mean depth of 4.0 m. In general, wind and tide are the major driving mechanisms of lake circulations. The lake has a diurnal tide with a mean range of 11 cm. Higher salinity waters from the Gulf of Mexico can enter the lake through three narrow tidal passes: the Rigolets, Chef Menteur, and a man-made Inner Harbor Navigation Canal (IHNC). Freshwaters can discharge into the lake through the Tchefuncte and Tangipahoa Rivers, the adjacent Lake Maurepas, and from runoff surrounding the lake. Therefore, the salinity distribution of the lake is governed by the saltwater fluxes from the three tidal passes, and the freshwater inputs.

In response to the high flood stage of the Mississippi River and to protect the city of New Orleans, the Bonnet Carré Spillway (BCS) was built between 1929 and 1936. The spillway diverts Mississippi River flood waters to the Gulf of Mexico via Lake Pontchartrain. The design capacity of the spillway is 7080 m^3/s. It was first operated in 1937 and eight times thereafter (1945, 1950, 1973, 1975, 1979, 1983, 1997 and 2008). In 1997, the spillway opened during 3/17-4/18, and the maximum flow discharge was about 6800 m^3/s, and the averaged discharge was about 4358 m^3/s over 31 days. The total amount of sediment entering the lake was about 9.1 million tons, more than 10 times as much as the normal yearly sediment loads of the lake. The suspended sediment concentration at the spillway gate was about 240mg/l.

Fig. 1 shows the bathymetry of Lake Pontchartrain. In general, the lake is very shallow, and the deeper parts are located near the tidal passes. Based on the bathymetric data, the computational domain was divided into a number of grids using the CCHE Mesh Generator (Zhang and Jia, 2009). In the horizontal plane, the computational domain was represented by a 224×141 irregular structured mesh.

Model calibration

The period from March 1-31, 1998, was selected for model calibration. In this period, the water movements within the lake are primarily wind- and tide-induced. As shown in Fig.1, two narrow passes - the Rigolets and Chef Menteur, were set as tidal boundaries. Due to the lack of measured elevation data at Chef Menteur Pass, the Rigolets data obtained from USGS was used (McCorquodale et al., 2005). The wind speeds and directions at the New Orleans International Airport obtained from the National Climatic Data Center, NOAA, were used for model simulation. For calibration runs, a few parameters, such as drag coefficient C_d, Manning's roughness coefficient, etc., were adjusted to obtain a reasonable reproduction of the field data provided by USGS. In this study, $C_d = 0.001$ and Manning's roughness coefficient = 0.025. Simulated water surface elevations and depth-averaged velocities were compared with the field data provided by USGS. Fig.2 shows the simulated and measured water surface elevations at the Mandeville

Station. Figs. 3a and 3b show the simulated and measured depth-averaged velocities in *x* and *y* directions at the South Lake Site, respectively. In general, the flow fields produced by the numerical model were in good agreement with field measurements.

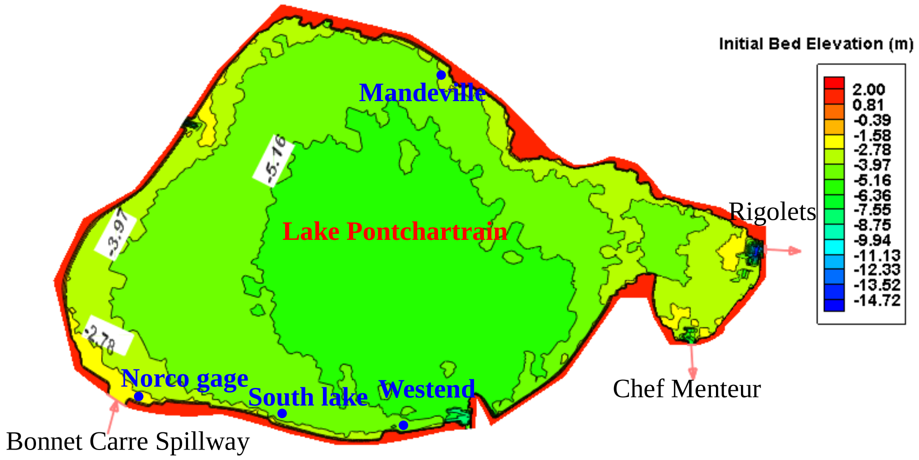


Fig. 1. The bathymetry of Lake Pontchartrain

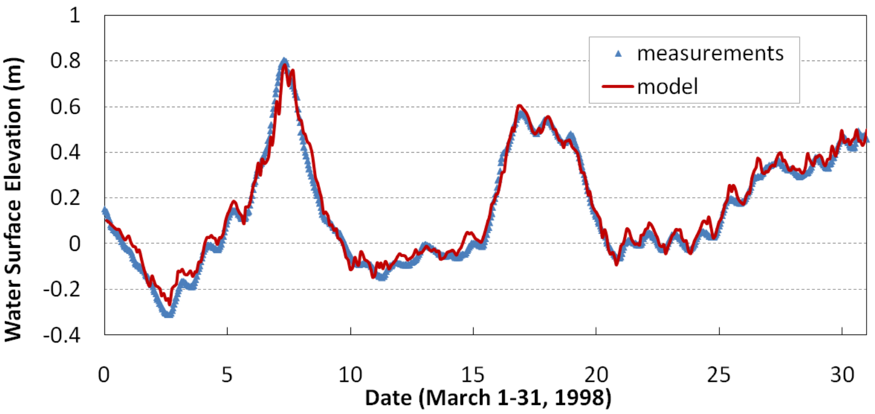


Fig.2. Simulated and measured water surface elevations at the Mandeville Station

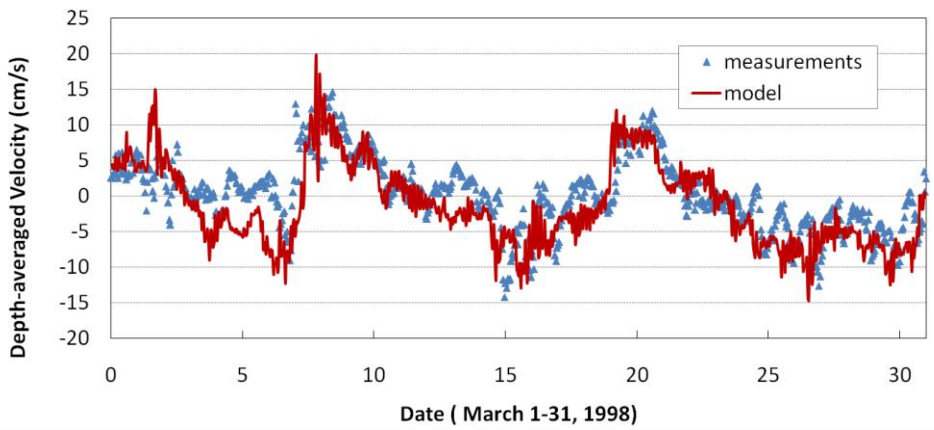


Fig. 3a. Simulated and measured velocities in west-east direction at the South Lake Site

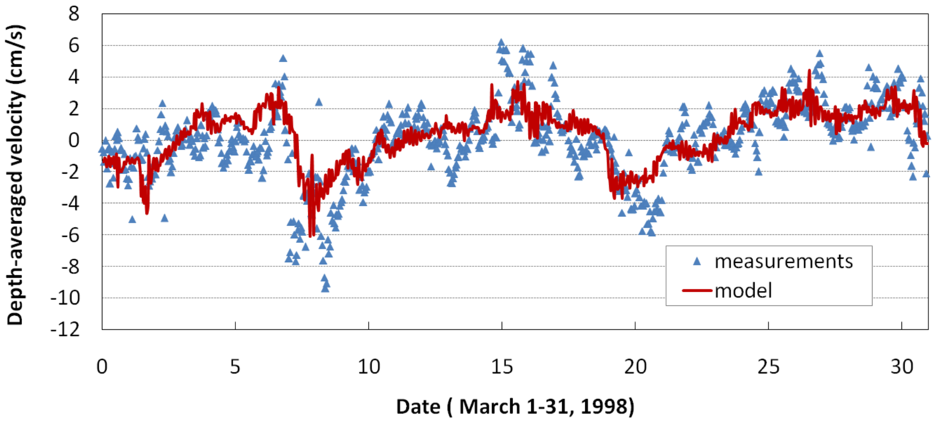


Fig. 3b. Simulated and measured velocities in south-north direction at the South Lake Site

Modeling the suspended sediment and salinity during the BCS opening for 1997 flood release

The calibrated model was applied to simulate the lake flow fields, sediment transport and salinity distribution during the BCS opening between 3/17-4/18, 1997. In this period, the averaged discharge was about 4358 m^3/s, and the maximum flow discharge was about 6800 m^3/s. The spillway partial opening was completed on March 27. The US Army Corps of Engineers (USACE) began to close the spillway on April 2, and it was completely closed by April 18. During this period, the averaged suspended sediment concentration at the spillway gate was about 240mg/l. The flow hydrograph and sediment concentration were set as inlet boundary conditions at BCS. The water surface elevations at Rigolets and Chef Menteur Pass obtained from USGS were set as tidal boundaries. At these two tidal boundaries, the salinity time series were specified based on the data provided by USGS. The wind speeds and directions at the New Orleans International Airport were used for model simulation.

Fig. 4 shows the flow circulations in Lake Pontchartrain when the spillway opened completely. The flow discharge over the spillway dominated the lake hydrodynamics and caused the entire lake water to be moved eastward through Rigolets and Chef Menteur Pass into the Gulf of Mexico. The flow pattern was completely different from the one induced by tide and wind.

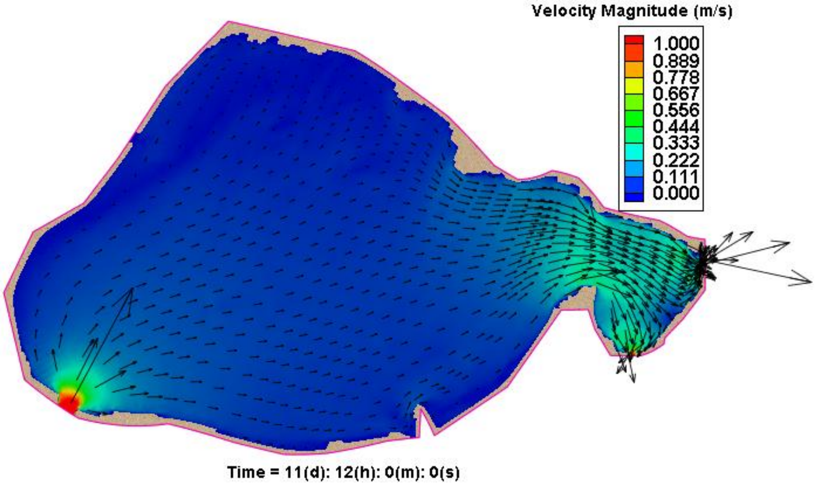
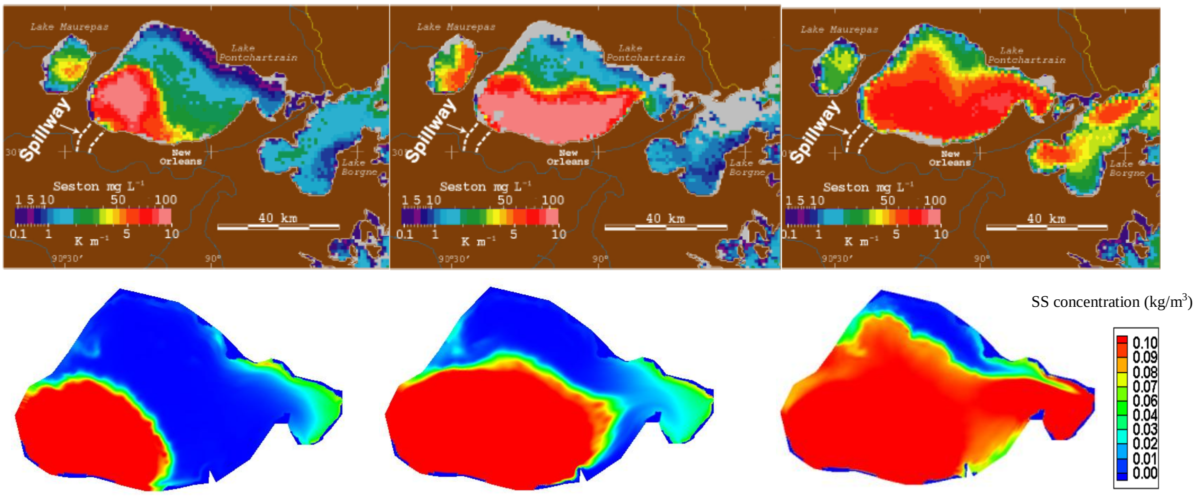


Fig. 4 shows the flow circulations in Lake Pontchartrain

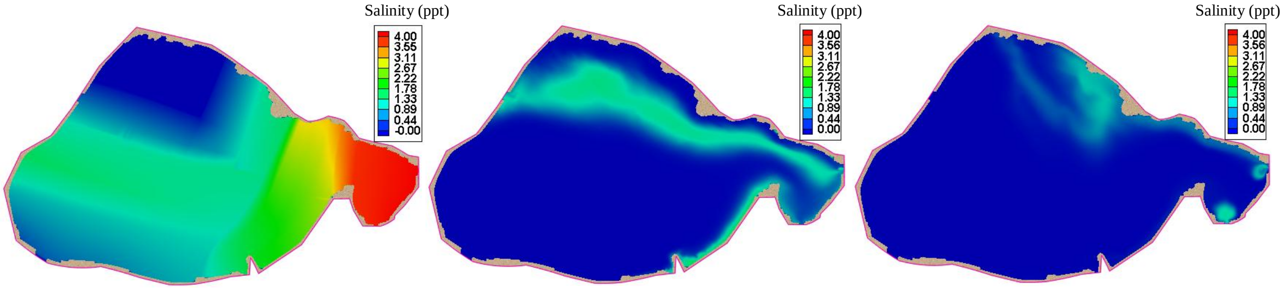
Fig.5 shows the comparisons of suspended sediment (SS) concentration obtained from numerical model and remote sensing imageries provided by NOAA. The simulated suspended sediment concentrations are generally in good agreement with satellite imageries. The numerical results and satellite imageries show that a large amount of sediment discharged into the lake, moved eastward along the south shore and gradually expanded northward, eventually affecting the entire Lake after one month of diversion.



3/24/97 **3/26/97** **4/7/97**

Fig. 5 Comparisons of simulated SS concentration and remote sensing imageries

Fig. 6 shows the simulated salinity distributions in the lake. Due to a large amount of fresh water discharged into the lake, the salinity in the lake decreased significantly. In the south area of the lake, the salinity reduced to near zero. At the Rigolets and Chef Menteur Passes, the salinity reduced from 4.5 ppt to less than 1 ppt.



3/17/97 (initial) **4/2/97** **4/17/97**

Fig. 6 Simulated salinity distributions

Environmental Impact of BCS Flood Release on Lake Pontchartrain

During the BCS opening, a large amount of fresh water and sediment discharged from the Mississippi River into Lake Pontchartrain and then into the Gulf of Mexico for one month of diversion. Based on the inlet discharge, it was estimated that the total volume of sediment-laden water entering the lake was about two times of the lake's volume, and the total amount of sediment was about 9.1 million tons. Numerical results show that the flow fields of the lake changed completely. The water and sediment first moved eastward along the south shore and gradually dispersed northward (Figs 4 and 5). The fresh water dominated the whole lake during this period. It was found that the lake salinity reduced significantly, except the tidal inlet boundaries, and a small area in the north of the lake, the salinity of the entire lake was reduced to zero (Fig. 6). A lot of sediment deposited into the lake or was transported into the Gulf of Mexico. The contaminated sediment from Mississippi River could bring a lot of pollutants, such as nutrients, Al, Cu, Cr, Hg, Pb, Zn, etc., to the lake, and caused a lot of environmental problems to its ecosystem.

Algal bloom

The nutrient levels in the Mississippi River were much higher than those in Lake Pontchartrain. When a flood is released, the river water with higher nutrient concentrations discharged into the lake, and affected the growth of algae.

The growth rate of algae (G_x) is determined by the availability of nutrients, the intensity of light, and ambient temperature. The effects of each factor are considered to be multiplicative:

$$G_x = P_{mx} f_N f_I f_T \tag{8}$$

in which P_{mx} is the maximum algae growth rate; f_N, f_I and f_T are the limitation factors due to nutrient availability, light intensity, and temperature, respectively. f_N can be calculated based on Michaelis-Menten Equation and Liebig's law of the minimum (Wool et al., 2001):

$$f_N = \min\left(\frac{DIN}{DIN + K_{mN}}, \frac{DIP}{DIP + K_{mP}}\right) \tag{9}$$

where DIN and DIP are the concentrations of dissolved inorganic nitrogen and dissolved inorganic phosphorus; K_{mN} and K_{mP} are the half-saturation constants for nitrogen and phosphorus uptake, respectively.

The light limitation factor f_I is obtained by integrating the Steele equation over depth and time (Chapra 1997):

$$f_I = \frac{2.72 f_d}{K_e \Delta z}\left[\exp\left(-\frac{I_0}{I_m} e^{-K_e (zd+\Delta z)}\right) - \exp\left(-\frac{I_0}{I_m} e^{-K_e \cdot zd}\right)\right] \tag{10}$$

in which f_d is the fractional daylight; Δz is the model segment (spatial element) thickness; zd is the distance from the water surface to the top level of a computational element in the water; I_0 is the daily light intensity at the water surface; I_m is the saturation light intensity of phytoplankton; K_e is the total light attenuation coefficient, and it is determined by the effects of water, chlorophyll and suspended sediment, and can be expressed by (Chao et al. 2007):

$$K_e = K_0 + 0.0088 C_{chl} + 0.054 C_{chl}^{0.67} + 0.0452 c \tag{11}$$

where K_0 is the light attenuation by pure water; C_{chl} is the concentration of chlorophyll and c is the concentration of suspended sediment.

It was reported due to a flood release that the concentrations of DIN and DIP in the lake increased about 20 and 5 times, respectively. In Lake Pontchartrain, the low DIN/DIP ratios indicate that the nitrogen is the limiting nutrient for algae growth. The 20 times higher DIN level would greatly increase the algae growth rate.

Because suspended sediment (SS) concentration increases a lot due to a flood release, algae growth in the lake is restricted. As shown in Eq.(11), the light attenuation coefficient K_e increases due to higher SS concentration. Based on Eqs. (10) and (8), the light limitation factor f_I is small and the algae growth rate is also small. So there was no algal bloom observed in the lake during the BCS opening.

By the end of May, about one and a half month after the spillway was closed, the SS concentration recovered to normal. Due to high levels of nutrients and temperature, the growth rate of algae increased and led to an explosion of blue-green algae (cyanobacteria). The peak of the algal bloom observed in mid-June, about two months after the spillway closed. The blooms produced high levels of heptatoxins which were measured during the peak of the blooms with traces persisting into the fall (Dortch et al., 1998). Fig. 7 shows the remote sensing imageries of algal bloom observed in Lake Pontchartrain (Penland et al., 2002). It can be found that algal blooms occurred in a large area of the lake. The blooms caused decreases of dissolved oxygen in the lake, and fish kills occurred in some places in June and July.

Fish habitat

It was estimated that about 9.1 million tons, more than 10 times as much as the normal yearly sediment load, entered Lake Pontchartrain in the 1997 flood release. Many of them deposited into the lake and changed the bed form of the lake. Field observations and numerical results show that the flow pattern of the lake changed completely, and the salinity in the lake decreased significantly. Based on the field observation, it took more than half a year for salinity to recover from the opening of the BCS. Lake water temperature was also decreased due to the colder river water. Those changes greatly affected the fish habitat, and caused negative impacts to oyster beds and fishery nursery grounds in the lake. In response to the dynamic changes in the salinity, temperature and water surface elevation in the lake, it was observed that some species, particularly brown shrimp, shifted and moved. It may take a long time for the fisheries resources to recover from the flood release event.

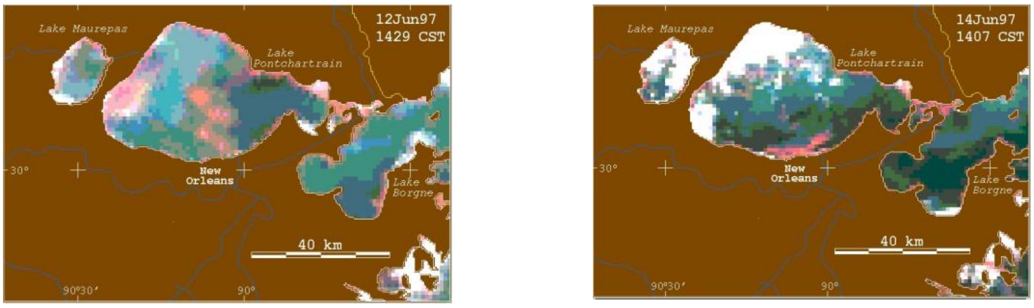


Fig. 7 The remote sensing imageries of algal bloom in Lake Pontchartrain (Penland et al., 2002)

Conclusions

A two-dimensional, depth-averaged numerical model was applied to simulate the flow circulations, salinity and sediment distributions in Lake Pontchartrain during a flood releases from the Mississippi River. The numerical results are generally in good agreement with field measured data provided by USGS and USACE, and satellite imageries provided by NOAA. In the flood release event, a vast amount of fresh water, sediment and nutrients were discharged into Lake Pontchartrain from the south-west corner, then moved eastward along the south shore and gradually dispersed northward, and eventually flow out of the lake. This event caused many environmental problems in the lake. The dispersion and transport processes of the sediment and salinity in the lake were studied with numerical simulation. The environmental and ecological impacts of the flood event on Lake Pontchartrain were studied. It was observed that the algal bloom occurred after the spillway closed for one and a half month, and the peak of the algal bloom was observed after the spillway closed for two months. This is consistent with the simulation results that high algae growth rate could occur only after flood release induced sediment concentration decreased. The fish habitat was also affected due to the dynamic changes of water surface elevation, salinity, etc. More detailed study on the ecosystem impact will be reported in the near future.

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