Water Quality Modeling in Support of the Mississippi Sound Coastal Improvement Program

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ABSTRACT

Mississippi Sound of the northern Gulf of Mexico extends from Lake Borgne in Louisiana on the west to Mobile Bay in Alabama on the east. Cat, Horn, Petit Bois, and Dauphin are the main islands. The total surface area of Mississippi Sound is approximately 500,000 acres; 25 percent is classified as near shore habitat with less than two meters (6.5 feet) deep, and 75 percent is offshore habitat.

In response to major damages on the Mississippi coast caused by Hurricane Katrina, Congress has directed the U.S. Army Corps of Engineers to conduct the Mississippi Sound Coastal Improvements Program (MSCIP), which is an analysis and design for comprehensive improvements, or modifications to existing improvements, in the coastal areas of Mississippi in the interests of: (1) hurricane storm damage reduction, (2) prevention of saltwater intrusion, (3) preservation of fish and wildlife, (4) prevention of erosion, and (5) other related water resource purposes. Several measures are under consideration for restoring resources along the coast including: construction of dunes, seawalls, and levees on shore; development of surge mitigation measures; wetland and ecosystem restoration; barrier island and beach restoration; and freshwater diversion.

Mathematical models are being used within MSCIP to help evaluate the effects of barrier island restoration and freshwater diversions. This paper describes the application of a three-dimensional water quality model of the Mississippi Sound region to evaluate the impacts of freshwater diversion alternatives on water quality.

The water quality model (WQM), which is based on the CE-QUAL-ICM water quality model code, is coupled to output from a three-dimensional hydrodynamic model of the region, which is based on the CH3D hydrodynamic model. The version of CH3D with sigma coordinates in the vertical dimension is being used. The model grid extends seaward beyond Chandelier Island and includes Mobile Bay, Lake Borgne, Lake Pontchartrain, the Inner Harbor Navigation Channel of New Orleans, and the Mississippi River Gulf Outlet channel.

Predicted water quality constituents, including nutrients, phytoplankton, dissolved oxygen, temperature, salinity, and underwater light intensity, are being evaluated for each alternative and compared to modeled existing, baseline conditions to assess relative changes. Output from the model also will be available for use in habitat quality evaluations.

Keywords: Freshwater Diversions, Nutrients, Surface Water, Numerical Models

Introduction

In response to major damages on the Mississippi coast caused by Hurricane Katrina, Congress has directed the U.S. Army Corps of Engineers to conduct the Mississippi Sound Coastal Improvements Program (MSCIP), which is an analysis and design for comprehensive improvements, or modifications to existing improvements, in the coastal areas of Mississippi in the interests of: (1) hurricane storm damage reduction, (2) prevention of saltwater intrusion, (3) preservation of fish and wildlife, (4) prevention of erosion, and (5) other related water resource purposes. Several measures are under consideration for restoring resources along the coast including: construction of dunes, seawalls, and levees on shore; development of surge mitigation measures; wetland and ecosystem restoration; barrier island and beach restoration; and freshwater diversion.

Freshwater diversions will not only lower salinity, but can also increase nutrient and suspended solid concentrations due to anthropogenic loadings into major rivers, such as the Mississippi River, that may be used for such diversions. Higher nutrient concentrations, primarily nitrogen, can fuel larger phytoplankton blooms. Increased suspended solids and phytoplankton biomass can reduce the amount of light available for submerged aquatic vegetation (SAV), which is important as habitat for living resources. Increased eutrophication, concomitant with more turbid water and elevated algal concentrations, is generally considered undesirable for environmental quality. There is also the possibility of lower dissolved oxygen during periods when the water column may stratify. Thus, any considerations for freshwater diversions should include an analysis of the impacts on water quality.

The objective of this study was to develop and apply a water quality model of the Mississippi Sound and surrounding region to provide key information for evaluating coastal restoration and improvement alternatives. The results presented in this report focus on the water quality conditions that could be imposed with three freshwater diversion alternatives that are being considered.

The scope of this study was limited to providing enough information to allow for screening of alternatives and evaluating the sensitivity of the system to diversions, not to provide refined forecasts of future water quality conditions with diversions. The model will require more attention to provide refined forecasts, and such effort may be warranted if preferred alternatives progress to a more in-depth level of analysis and plan formulation.

Three-dimensional (3D) hydrodynamic (CH3D-sigma level vertical coordinates) model code was used for the hydrodynamic model (Chapman et al. 1996), and the CE-QUAL-ICM (ICM) model code was used for water quality. The modeling grid, shown in Figure 1, consists of 172 x 405 rows and columns and 40,406 active computational cells in plan-form. Five vertical sigma layers were used resulting in a total of 202,030 active cells. ICM was first developed for Chesapeake Bay (Cerco and Cole 1993) but has subsequently been used for many diverse systems. A more recent version of ICM (Cerco et al. 2004) was used for the present study. A detailed description of this version of ICM is described in the report by Cerco et al. (2004).

Given the limited data availability and the limited scope of this study, some of the more comprehensive WQM routines were not activated, such as the sediment diagenesis, benthic algae, and submerged aquatic vegetation (SAV) routines. For these routines to provide added value, it would be necessary to simulate a multi-year period. Typically five or more years of simulation are required for bottom sediments to re-equilibrate for changing nutrient loads. Given the size of this grid, this would have required significant supercomputing requirements and a longer study time with greater funding. Additionally, much more observational data would have been required for model calibration and validation than was available. The results of the WQM should still be representative of future alternative conditions given the mostly unstratified conditions of the Sound, which diminishes the importance of sediment nutrient processes and their influence on the water column. The model also provides underwater light attenuation that can be used to infer impacts on SAV, which is of interest for habitat. If other model compartments are needed in a future study, they can be activated at that time.

Additional inputs of freshwater flows and tributary nutrient loads were included as required after extending the model domain. Model calibration was conducted again using the spring-summer 1998 conditions and observations, as was used for the Gulfport study. The WQM was executed for April 1 through September 30, 1998, conditions when running baseline and scenario alternatives. The HM was run for the same period, except the month of March was also included to improve model spin-up.

Water Quality Model Description

CE-QUAL-ICM (ICM) was designed to be a flexible, widely applicable, state-of-the-art eutrophication model. Initial application was to Chesapeake Bay (Cerco and Cole 1993). Since the initial Chesapeake Bay study, the ICM model code has been generalized with various revisions and improvements. Subsequent additional applications of ICM included the Delaware Inland Bays (Cerco et al. 1994), Newark Bay (Cerco and Bunch 1997), the San Juan Bay Estuary (Bunch et al. 2000 and Cerco et al. 2003), Florida Bay (Cerco et al. 2000), St. Johns River (Tillman et al. 2004), Pascagoula River Harbor (Bunch et al. 2003), Lake Washington (Cerco et al. 2004), and the Port of Los Angeles other sites. Each model application employed a different combination of model features, and some applications required the addition of new capabilities to more fully capture the system dynamics.

ICM requires the flow data using a hydrodynamic model such as CH3D. Hydrodynamic variables (i.e., flows, vertical turbulent diffusion coefficients, and volumes) must be specified externally and read into the model. Hydrodynamics may be specified in binary or ASCII format and are usually obtained from a hydrodynamic model such as the CH3D model.

A limited number of variables and only one algal group were activated due to the limited amount of observed data needed for model calibration. Particulate organic components were lumped into a single labile compartment for each major nutrient. Inorganic suspended solids were included in addition to organic solids and algae due to the interest in changes in the light climate or light attenuation resulting from the introduction of additional freshwater that can result in elevated suspended solids concentrations. For this study, 14 state variables of ICM were activated and are listed in Table 1.

Table 1. Water quality model state variables for Mississippi Sound model.

Temperature	Salinity
Fixed Solids (inoranic suspended solids)	Dissolved Oxygen (DO)
Dissolved Organic Carbon (DOC)	Particulate Organic Carbon (POC)
Ammonium (NH4) Nitrogen	Nitrate + Nitrite Nitrogen (NO3)
Dissolved Organic Nitrogen (DON)	Particulate Organic Nitrogen (PON)
Total Phosphate or total inorganic phosphorous (TIP)	Dissolved Organic Phosphorus (DOP)

Model Input Data

The WQM requires loadings and boundary conditions, initial conditions, and model parameters including various process rate coefficients. The WQM inputs are described within this section.

Loadings and Boundary Concentrations

Loadings for all sources of nutrients and sediment must be specified for the model. These include loadings from inflowing rivers, atmospheric deposition, and other sources, such as local distributed runoff and major point source (e.g., waste water discharge) loadings. Of these, the primary inputs are from rivers and the atmosphere, thus, loadings from local distributed runoff and point source waste water discharges, including storm water drains, were not included in the model for this study. Methods for deriving estimates for riverine and atmospheric loadings are discussed in this section.

Additionally, boundary concentrations must be specified along all boundary flow faces for all water quality state variables, unless a variable is treated as a point source load instead as done for some rivers as explained below. Open water (ocean) boundary concentrations must be specified for all state variables. Boundary concentration data for rivers and ocean are also discussed and presented within this section.

River Boundary Concentrations and Loadings

River loadings can be specified either of two ways in the model. One way is to specify the concentrations at the model boundaries where the river flows enter. This approach requires that the boundary has flows from the hydrodynamic model. The product of flow and concentration is load (mass/time). The other approach is to specify the loading as a point source load (kg/day) for the model cell where the river enters. This approach does not require a flow from the hydrodynamic model at the boundary although flows are provided for all major inflowing rivers in this study. River boundary concentrations should be set to zero for all state variables that are treated as point source loads. Both methods were used for this model study for nutrients. Some water quality variables are best specified as a concentration at the river inflow boundary, such as temperature, dissolved oxygen, and salinity. Salinity was set to 0.0 parts per thousand (ppt) for all river inflow boundaries. Other water quality variables are best specified as loads, such as nutrients, if data are available to determine loads. The boundary conditions for each river inflow are explained below. The rivers included in the model are shown in Figure 1. Data used in this study are provided in Dortch et al. (2007).

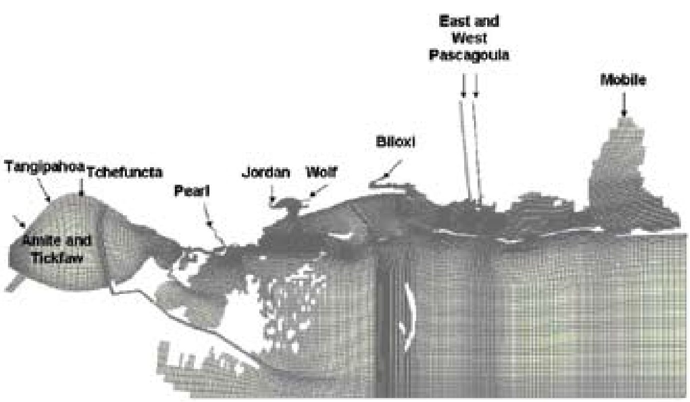

Figure 1. Locations of rivers included in the model.

Atmospheric Loadings

Goolsby et al. (1999) summarizes a literature review of atmospheric loading of nitrogen to the Gulf of Mexico. They report that wet deposition of N is an order of magnitude or more than dry deposition, thus, dry deposition can be ignored. Goolsby et al. (1999) report that the average wet deposition of inorganic N along the U.S. Gulf Coast is typically on the order of 3 to 4 kg/ha/yr with NO_3 accounting for about 60% of total N deposited. Using a value of 3.5 results in 2.1 and 1.4 kg/ha/yr for NO_3 and NH_4, respectively. If these loadings are applied to the surface of Lake Pontchartrain with an area of 1,632 km^2 (Penland et al. 2002), a loading of 0.34 and 0.23 Mkg/yr for NO_3 and NH_4, respectively, can be calculated and are less than half the values reported in Table 3-6. Goolsby et al. (1999) report that N loadings approach 7 kg/ha/yr for Gulf waters near southern Louisiana. They also state that values are higher closer to shore than out in the Gulf, with values of about 5.5 kg/ha/yr. Thus, a value of 5.5 was used for atmospheric TN loading in the model, which was entered as 3.3 and 2.2 kg/ha/yr NO_3 and NH_4, respectively. This TN loading from the atmosphere distributed over the model domain of 17,280 km^2 is about a fourth as large as the TN loadings from the tributaries entering the model domain.

Out Gulf Boundary Concentrations

The U.S. Environmental Protection Agency (EPA) collected water quality data off-shore in Mississippi Sound during July 2002 at four stations (MS1, MS2, MS3, and MS4), which are shown in Figure 2. These data along with various assumptions were used to estimate the outer Gulf boundary conditions for water quality.

Variations in water quality variables over the depth were assumed to be small along the outer Gulf boundary, thus, a single value for each variables was assigned for each vertical layer of the model along the boundary. Temperature and DO were varied over time along the outer Gulf boundaries,

Figure 2. EPA sampling stations for July 2002.

but other constituents were held constant over time. There are two outer Gulf boundaries, one along the south boundary running east-west outside the barrier islands, and one running north-south from the south boundary to the shore east of Mobile Bay. The same water quality boundary concentrations were used for both boundaries.

The same temperatures as used for the outer Gulf boundaries in the Gulfport Harbor model study (Bunch et al. 2005) were used in this study for those boundaries. Salinity values along the two boundaries were the same as those used for the hydrodynamic model in this study along those boundaries, which were varied spatially (increasing salinity moving east and south) but held constant over time. Algal chlorophyll a concentrations are typically on the order of 1.0 μg/L in the open ocean or sea away from the shore, so this value was assumed for the outer Gulf boundaries. The TOC measured at the EPA stations was 1.0 mg/L, so this was the value assumed for DOC with POC set to zero along the boundaries. No values were measured at the EPA stations above the detection limit of 0.05 mg/L N for nitrate + nitrite nitrogen and ammonium nitrogen. Therefore, the open Gulf boundary values for these two water quality variables were set to 0.05 mg/L. Measured values for TKN at the EPA stations averaged 0.62 and 0.14 mg/L N for the western (MS1 and MS2) and eastern (MS3 and MS4) stations, respectively. The western stations are more heavily influenced by terrestrial loadings from tributaries entering in that region, whereas the eastern stations are more representative of conditions in the open Gulf. Thus, a value of 0.14 mg/L for TKN was used to estimate TON, or DON since PON was assumed to be zero along the outer Gulf boundaries. With ammonium of 0.05 mg/L and TKN of 0.14 mg/L, the calculated DON was 0.09 mg/L, which was applied along the outer Gulf boundaries. TP and total dissolved phosphorus (TDP) were measured at the EPA stations, but all values were below the detection limit of 0.025 mg/L P except for TP values that averaged 0.033 mg/L at the western stations. Thus, it was assumed that the phosphorus along the outer Gulf boundaries was TIP with a value of 0.025 mg/L. The DO concentrations for the outer Gulf boundaries were set equal to the computed DO saturation based on water temperature. TSS was measured at the EPA stations, but with the exception of one value of 8.0 mg/L at Station MS1, the other values were close to or below the detection limit of 4.0 mg/L. Thus, the outer Gulf boundary concentration for ISS was set to half the EPA station values, or 2.0 mg/L, since very little TSS would be expected this far out.

Initial Conditions

Initial conditions for water quality constituents were first set equal to those used for the Gulfport Harbor model study (Bunch et al. 2005), which were based upon observed data from MSDEQ. These initial concentrations for the water column (Dortch et al. 2007), were specified as uniform throughout the grid, i.e., same values for all cells in all layers. To provide more realistic, spatially varied, initial conditions, ICM was run for one month using the uniform initial conditions discussed above. Hydrodynamics and water quality boundary conditions for April 1998 were used for this run. Water quality concentrations at the end of the month for all computational cells were saved to a file and were used as the initial conditions for a second month-long run, again using April 1998 hydrodynamics and water quality boundary conditions. The end of month concentrations were again saved for all cells and used as initial conditions for a third month-long run with the same hydrodynamics and water quality boundary conditions. Thus, three one-month-long runs were used to spin-up the initial conditions for water quality that were used for all subsequent model calibration and scenario runs.

Other Inputs

The ICM model requires various kinetic rate coefficients and other parameters to simulate water quality processes. All model parameters are described by Cerco et al. (2004) or in the draft user manual that was developed as a part of that study. Model parameters that were used for the final model calibration in the present study are presented in the Chapter 4 on Model Calibration.

Additionally, meteorological data are required for predicting temperature and photosynthetically active radiation (PAR), which affects plant growth. The model uses daily solar radiation incident on the water surface, equilibrium temperatures, and heat exchange coefficients (Edinger et al. 1974) to predict water temperature. These three variables are computed from a pre-processor program using meteorological data consisting of air temperature, dew point temperature, wind speed, and percent cloud cover. If measured solar radiation is available, then measured values can be used rather than computed values. Daily solar radiation is converted in the model to PAR for use in plant growth routines. Solar radiation and PAR are attenuated over the water depth due to water quality properties, including suspended solids and algal concentrations, for use in temperature simulation and plant growth. Meteorological data for 1998 from the airport in Mobile, AL, were used in this study. These meteorological data were obtained from the Air Force Combat Climatologic Center.

Model Calibration

A partial model calibration was performed due to the limited scope of this study. Hydrodynamics from CH3D were supplied to the WQM for March through September 1998 conditions. The WQM was executed for the period April through September 1998 for calibration.

Model calibration proceeded by making a limited number of runs with various adjustments to model kinetic coefficients and parameters. The primary parameters that were varied in the calibration simulations were particulate organic nitrogen and phosphorus hydrolysis rates, the dissolved organic nitrogen and phosphorus mineralization rates, the maximum nitrification rate, the suspended solids and algal settling rates, fractions of algal recycling and proportioned to various organic pools, carbon to chlorophyll ratio, algal half saturation constants for nutrient uptake, maximum photosynthesis rate for algal growth, and first order algal predation rate. The calibration was particularly sensitive to the mineralization and nitrification rates.

Model results were compared to observed data obtained from Mississippi Department of Environmental Quality (MSDEQ) for various stations throughout the Sound. Observations were not available for all variables at all stations. Additionally, stations were added that did not have observational data.

As noted previously, only a partial model calibration was performed due to the limited scope of this study. Therefore, the calibration is not as good as usually achieved with this model. Additionally, this system is quite large and complex, which complicated identifying and quantifying all the loadings. The model presently contains tributary and atmospheric loadings. However, there are other loadings, such as combined storm water outlets, waste water discharges, and local runoff that are not accounted for in the model. Including these additional loadings would require a substantial amount of additional work and time. Additionally, there is considerable uncertainty in the loadings that were provided in the model due to the lack of data. There was no attention give to calibrating the model for the back bays, which can be sensitive to localized loadings. Given a larger study scope, it would be possible to focus more on the back bays and to add other observed data in the Gulf, such as data from the states of Alabama and Louisiana and possibly EPA and NOAA. Having additional data could help improve calibration.

Even though the calibration is not as complete as usually performed, the results are considered sufficient to meet the study objectives. The model can be used to make relative comparisons of water quality for diversion alternatives contrasted against baseline existing conditions, which is useful for evaluating the sensitivity of the system to freshwater diversions.

The model initial conditions were spun up one time during the first calibration run as explained in Dortch et al. (2007). These initial conditions were used for all subsequent runs including calibration and scenario runs. Ideally, the model's initial conditions should be spun-up for each new run whenever anything is changed in the model including calibration parameters and modified freshwater flows and loads. The additional spin-up runs were not conducted due to the need to meet the study schedule constraint. It can require a month or longer for the initial conditions to flush out, so some of the model results early in the simulation may not be as accurate as later in the simulation due to poor specification of initial conditions.

Scenario Results

The WQM was applied for three alternative scenarios: (1) diversion of freshwater flow from the Mississippi River at Bonnet Carre' spillway, (2) diversion of freshwater flow from the Mississippi River at Violet Marsh, and (3) diversion of all of the Escatawpa River flow into Grand Bay. The locations of the three diversions are introduced are shown in Figure 3. The Bonnet Carre' diversion varied by month and is shown in Figure 4. The Violet Marsh diversion was a constant flow of 212.4 cms (7500 cubic feet per second, cfs). The Escatawpa diversion is the flow that occurred in the Escatawpa River during 1998, and those values were varied daily in the model as shown in Figure 5. The WQM was applied for the period April through September 1998 using the same inputs as the final calibration run except for different hydrodynamics and different boundary conditions for the diverted flow

Figure 3. Observation station locations.

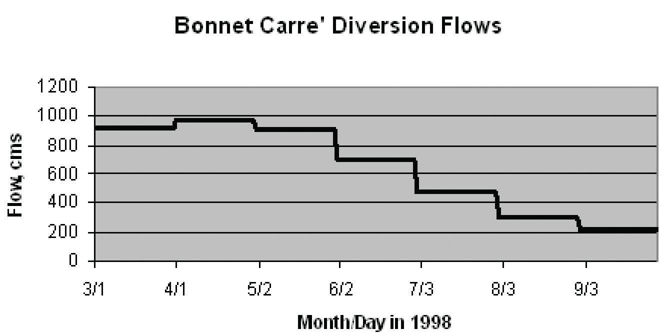

Figure 4. Bonnet Carre' diversion flows.

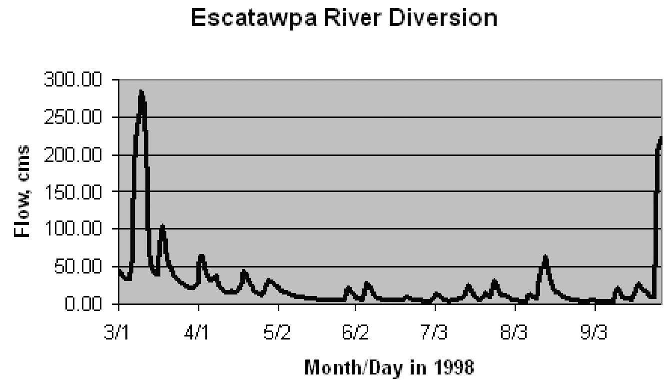

Figure 5. Escatawpa River diversion flows.

and associated concentrations of the flow. The HM was run with the same conditions as used for the base conditions used in the WQM calibrations for 1998 except that the additional freshwater flows were introduced. A separate HM run was made for each of the three diversions. The water concentrations characteristic of Mississippi River water, which were developed as discussed in Dortch et al. (2007), were associated with the first two freshwater diversion flows when executing the WQM. The water quality of the Pascagoula River was used for the Escatawpa diversion.

Results for the four scenarios (i.e., base, Bonnet Carre' diversion, Violet Marsh diversion, and Escatawpa River diversion) were post-processed to produce summer average (July - September) surface concentrations for 1998. The summer average results were computed for salinity, chlorophyll, light extinction, and TSS and are plotted as color contours in plan form throughout the model domain. These plots are presented for the four water quality constituents in Figures 6 – 9 where the four scenarios are grouped together in each figure for comparison.

Summer Average Concentration Contours

The effects of the Bonnet Carre' diversion are very apparent in the western portion the domain, whereas, in other parts of the domain, the changes are not as obvious unless one looks closely at the near shore conditions. It is interesting how the diversion tends to affect the water quality along the shore of Mississippi Sound, where the influence beyond the barrier islands can not be detected from the plots, except

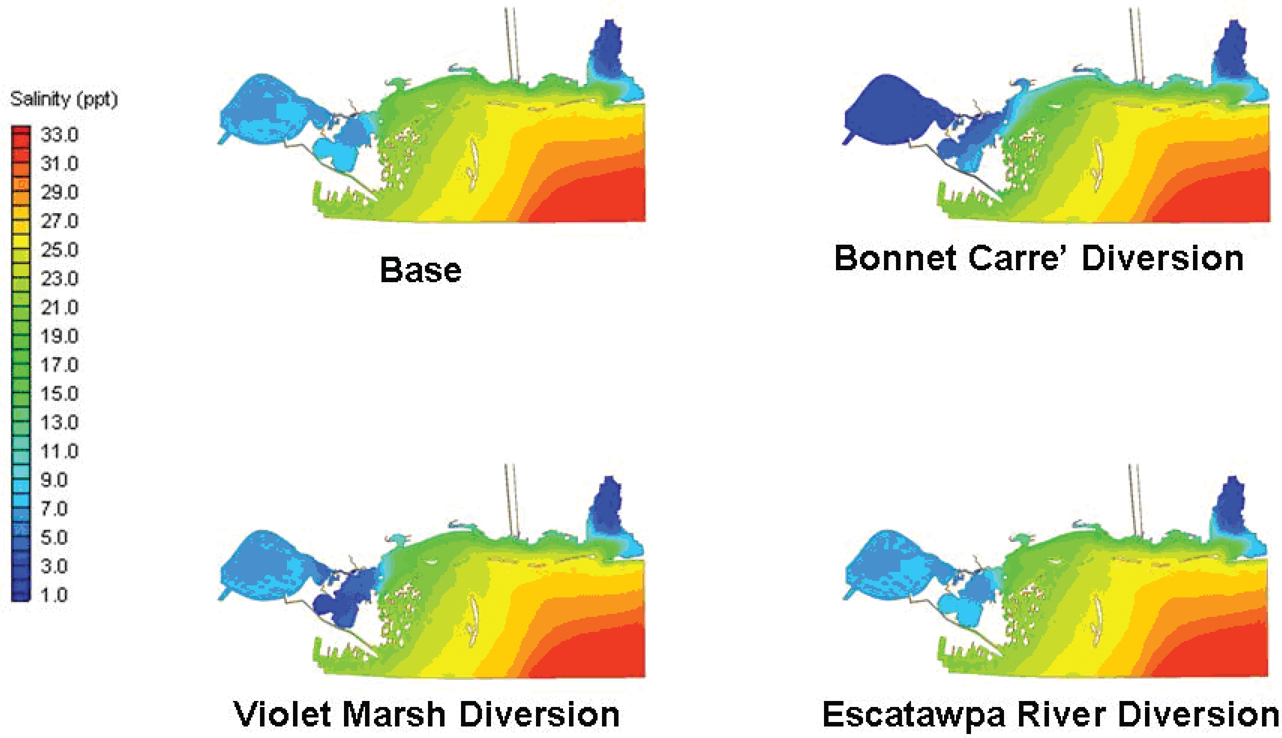

Figure 6. Summer average surface concentration contours for salinity for three conditions.

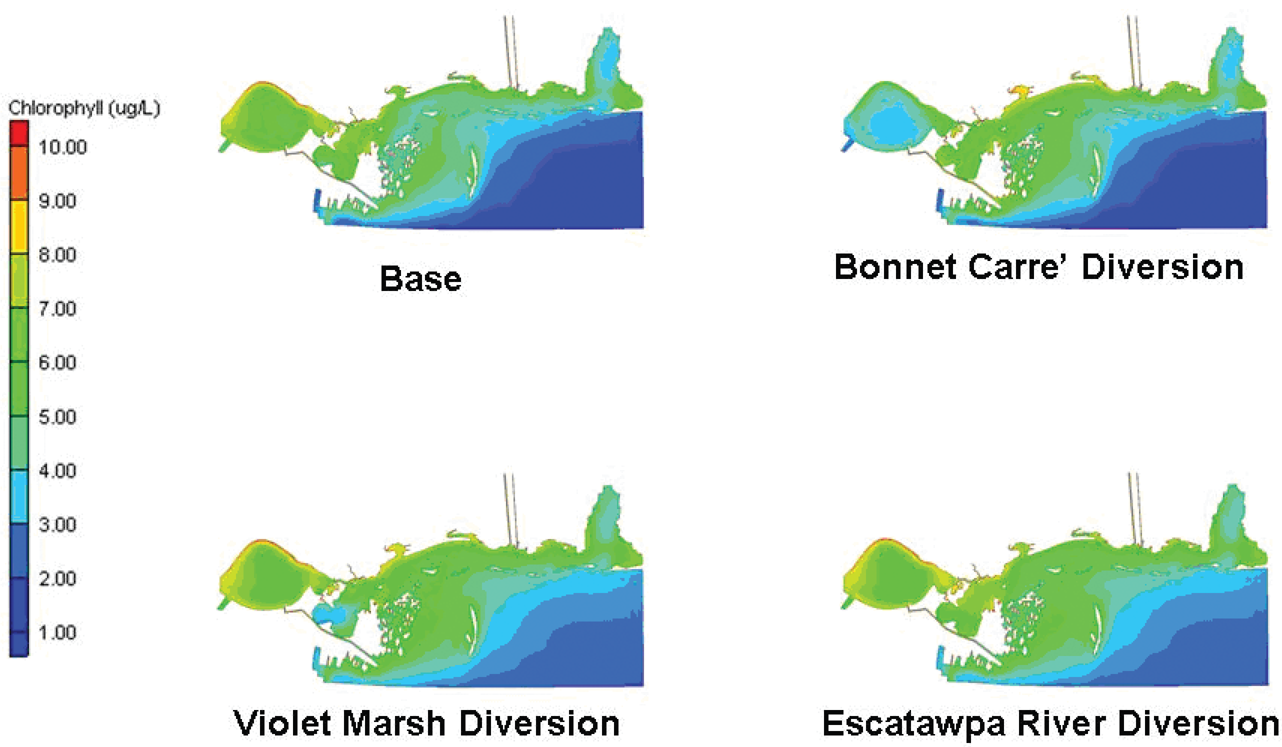

Figure 7. Summer average surface concentration contours for chlorophyll for three conditions

for possibly chlorophyll. The diversion has a fairly significant influence all along the coast from Lake Borgne to Mobile Bay. There is also an influence within the Mississippi River Gulf Outlet and where it empties north of Breton sound.

Similar to the Bonnet Carre' diversion, the effects of the Violet Marsh diversion are very apparent in the western portion the domain, whereas, in other parts of the domain, the changes are not as obvious unless one looks closely at the near shore conditions. The diversion tends to affect the water quality along the shore of Mississippi Sound, whereas the influence beyond the barrier islands can not be detected from the plots, except for possibly chlorophyll. This diversion elevates chlorophyll near the Chandeleur Islands, more so than the Bonnet Carre' diversion. The diversion influences water quality all along the coast from Lake Borgne to Mobile Bay, but not as much as the Bonnet Carre' diversion.

The summer average concentration contours also show that there is little, if any, difference in the results for the Escatawpa diversion and base conditions . The changes in water quality are limited to Grand Bay and the Mississippi shoreline west of Grand Bay. It is interesting how this diversion has any impact within Bay St. Louis although the impact is small. Salinity is decreased a few parts per thousand in Grand Bay and westward along the coast. Chlorophyll is increased slightly (less than 1 μg/L), as well as TSS (about 1 mg/L) in the same areas. Little to no change in light extinction occurred.

Conclusion

This model study indicates that freshwater diversions from the Mississippi River through either Bonnet Carre' Spillway or Violet Marsh will result in substantial changes in water quality. The effect of freshwater diversions are expected to be felt throughout much of the area along the coast even for relatively modest diversions (7500 cfs) introduced on the edges of the system (such as Violet Marsh). The changes in Mississippi Sound water quality resulting from these diversions will include lower salinity, higher concentrations of nutrients, TSS, phytoplankton, and TOC, and greater light extinction, thus, less light reaching the bottom. The latter change could impact SAV densities.

Figures 6 through 9 show the amount of change relative to the existing base conditions. In some cases, the change is quite dramatic. However, it is emphasized that the amount of water diverted can make a great difference. The amount of change for each diversion is directly proportional the amount of water diverted. Thus, the Bonnet Carre' diversion had a greater effect than the Violet Marsh diversion since the flows were greater for the former. Similarly, the Violet Marsh diversion had a much great difference than the Escatawpa River diversion for the same reason. The flows of the Escatawpa River were so low during April through September of 1998, that this diversion had little impact except within Grand Bay, where changes were relatively small and mostly confined near shore.

As with many model studies, results presented here should be treated as relative, rather than absolute forecasts. Thus, the water quality for diversions should be compared relative to the base conditions, rather than used as refined forecasts of future concentrations. This is particularly true for salinity and TSS since these two constituents of interest presented calibration challenges. A more detailed analysis with additional calibration work is expected to improve the accuracy of salinity predictions. Improving the accuracy of TSS predictions is more problematic given the paucity of data and lack of full understanding of processes affecting TSS in this system. Model enhancements and more detailed study would be required to refine the accuracy of the water quality model for forecasting absolute water quality conditions with diversions. Such refinement of the model should be considered if the MSCIP proceeds with more definitive plans for diversions.

Results from the water quality model can still be used to estimate changes in habitat for living resources of interest. The best approach with the present model is to delineate the areas that exhibit the water quality conditions required for acceptable habitat using model output for base conditions. Model output for alternative diversions can then be used to delineate areas of acceptable habitat with diversion. The areas where acceptable habitat has changed (gained or lost) can then be determined and shown. This approach is based on relative changes in water quality rather than absolute results.

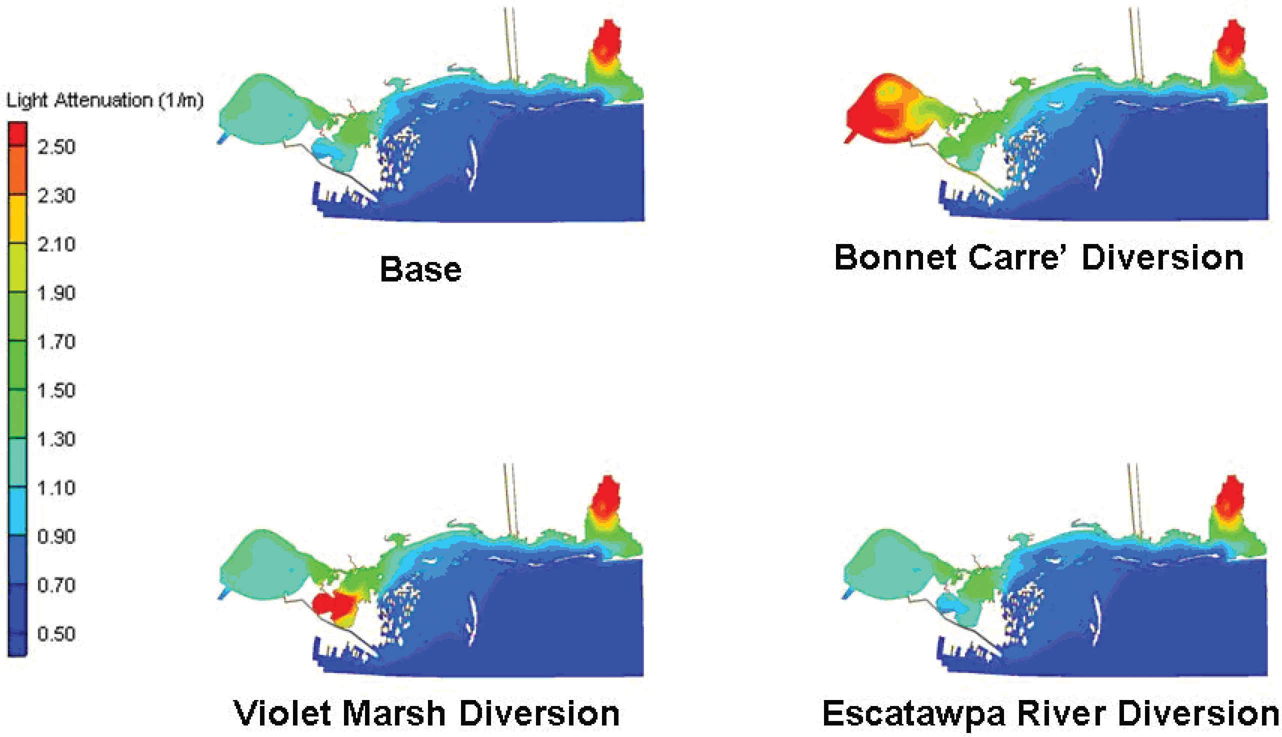

Figure 8. Summer average light extinction for three conditions.

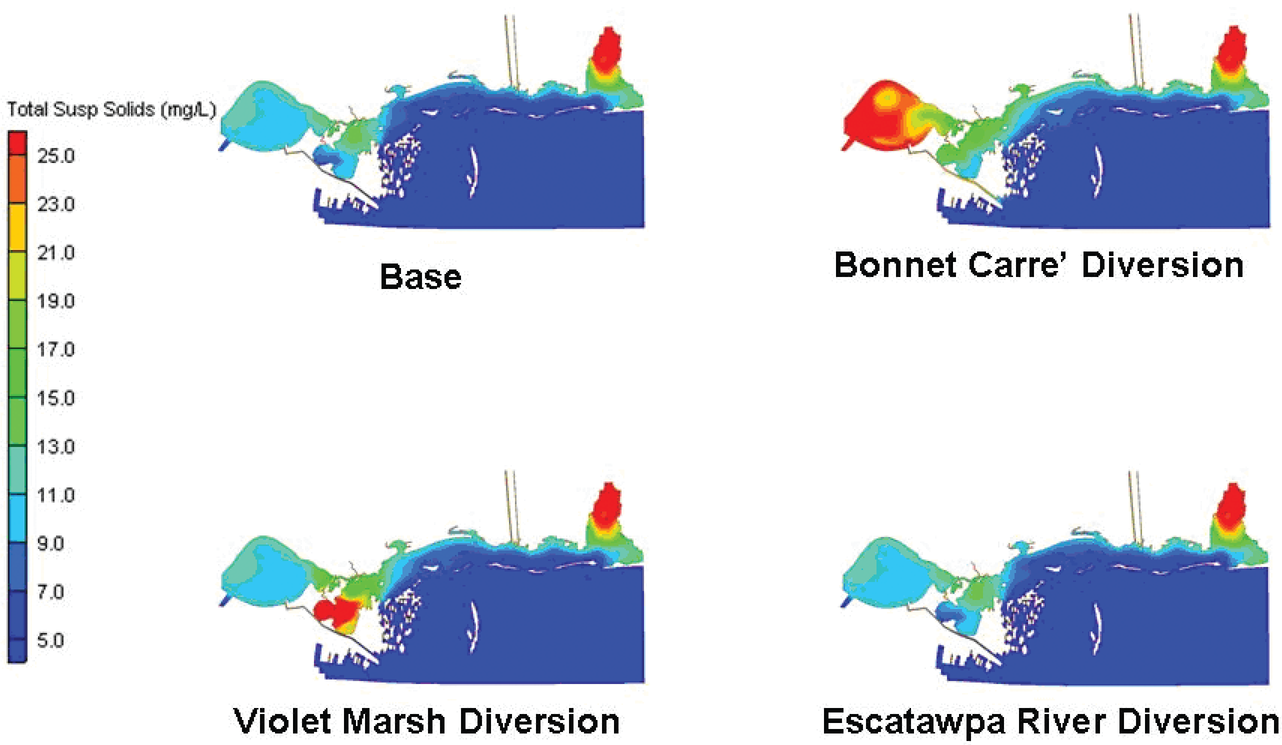

Figure 9. Summer average surface concentration contours for TSS for three conditions

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