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Predicted Impacts from Offshore Produced Water Discharges on Hypoxia in the Gulf of Mexico

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Abstract

Summer hypoxia (dissolved oxygen < 2 mg/L) in the bottom waters of the northern Gulf of Mexico has received considerable scientific and policy attention because of potential ecological and economic impacts. This hypoxic zone forms off the Louisiana coast each summer and has increased from an average of 8,300 km^2 in 1985–1992 to over 16,000 km^2 in 1993–2001, reaching a record 22,000 km^2 in 2002. The almost 3-fold increase in nitrogen load from the Mississippi River Basin (MRB) to the Gulf since the middle of the last century is the primary external driver for hypoxia.

A goal of the 2001 Federal Action Plan is to reduce the 5-year running average size of the hypoxic zone to below 5,000 km^2 by 2015. After the Action Plan was developed, a new question arose as to whether sources other than the MRB may also contribute significant quantities of oxygen-demanding substances. One very visible potential source is the hundreds of offshore oil and gas platforms located within or near the hypoxic zone, many of which discharge varying volumes of produced water.

The objectives of this study were to assess the incremental impacts of produced water discharges on dissolved oxygen in the northern Gulf of Mexico, and to evaluate the significance of these discharges relative to loadings from the MRB. Predictive simulations were conducted with three existing models of Gulf hypoxia using produced water loads from an industry study. Scenarios were designed that addressed loading uncertainties, settleability of suspended constituents, and different assumptions on delivery locations for the produced water loads. Model results correspond to the incremental impacts of produced water loads, relative to the original model results which included only loads from the MRB.

The predicted incremental impacts of produced water loads on dissolved oxygen in the northern Gulf of Mexico from all three models were small. Even considering the predicted ranges between lower- and upper-bound results, these impacts are likely to be within the errors of measurement for bottom water dissolved oxygen and hypoxic area at the spatial scale of the entire hypoxic zone.

Introduction

Summer hypoxia in the bottom waters of the northern Gulf of Mexico has received considerable scientific and policy attention because of potential ecological and economic impacts from this very large zone of low oxygen, and because of the implications for management within its massive watershed (1, 2). These regions of oxygen concentrations below 2 mg/L that form off the Louisiana coast each spring and summer increased from an average of 8,300 km^2 in 1985–1992 to over 16,000 km^2 in 1993–2001 (3), and reached a record 22,000 km^2 in 2002. There is significant inter-annual variability and no comprehensive records of areal extent exist prior to 1985. Figure 1 is a composite plot that shows the frequency of occurrence of mid-summer hypoxia in the Gulf of Mexico from 1985 to 1999.

An assessment of hypoxia causes and consequences (1, 3) concluded that the almost 3-fold increase in nitrogen load to the Gulf (4) is the primary external driver that stimulated the increase in hypoxia since the middle of the last century. This riverine nitrogen input stimulates coastal algal production and the subsequent settling of organic matter below the pycnocline. Because the pycnocline inhibits vertical oxygen flux, decomposition of organic matter below the pycnocline consumes oxygen faster than it is replenished, resulting in declining oxygen concentrations during the period of stratification.

The Federal-State-Tribal Action Plan for reducing, mitigating, and controlling hypoxia in the northern Gulf of Mexico (2) included a goal of reducing the five-year running average size of the hypoxic zone to below 5,000 km^2 by 2015. After the Action Plan was developed, a new question arose as to whether sources other than the Mississippi River Basin (MRB) may also contribute significant quantities of oxygen-demanding substances. One very visible potential source is the hundreds of offshore oil and gas platforms located within or near the hypoxic zone. Many of these platforms discharge varying volumes of produced water. Produced water is trapped in underground formations and is brought to the surface along with oil or gas.

Figure 2 (J.P. Smith, ExxonMobil Upstream Research Company, personal communication) shows the frequency of occurrence of mid-summer hypoxia superimposed on a lease block map of the Gulf of Mexico. The blue dots on the map show platforms in the region. There are an estimated 287 platforms in the hypoxia zone (5); however, not every platform is a produced water discharge point. The red boxes indicate the lease block areas that are in the hypoxic zone. Each box is marked with the number of lease blocks in the area that have produced water discharges and that are in the hypoxic zone.

Until recently, only limited data characterizing oxygen demand, nutrient concentrations and loadings from offshore produced water discharges had been collected. These discharges are authorized by a general permit issued by EPA under the National Pollutant Discharge Elimination System (NPDES). As part of the re-issuance of this permit in 2004, EPA required that the industry provide information on the amount of oxygen-demanding substances contained in the produced water discharges.

Objectives

The objectives of this study were to assess the incremental impacts of produced water discharges on dissolved oxygen conditions in the northern Gulf of Mexico, and to evaluate the significance of these discharges relative to loadings from the MRB. This study was conducted using the three existing models of Gulf hypoxia described in Scavia et al. (6). Results from this study will provide EPA with an initial assessment of the appropriate forward path for how to incorporate produced water discharges within the overall framework for controlling nutrient loadings to the Gulf of Mexico as a management tool for reducing the occurrence and extent of hypoxia.

This paper is based on a report submitted to EPA in July 2006 (7) and it contains the principal study results and conclusions. The complete study, including detailed descriptions of the models and all tabular and graphical results, is documented in the report to EPA.

Existing Models of Gulf Hypoxia

The three existing models of Gulf hypoxia (8, 9, 10, 11) capture very different aspects of the physics, chemistry, biology and ecology of the northern Gulf. Table 1 contains a summary of the principal attributes of each model in terms of spatial and temporal scales, nutrients, characterization of hypoxia and calibration time periods.

Loadings From Produced Waters

In response to a requirement of the NPDES general permit issued in 2004, industry and the Department of Energy (DOE) jointly funded a waste characterization study of produced water discharges to the Gulf of Mexico hypoxic zone (5, 12). This study involved a program to sample 50 offshore oil and gas platforms located within the hypoxic zone. The loadings for the 50 sampled platforms represent a produced water discharge volume of approximately 176,000 bbl/day. The total amount of produced water generated in the hypoxic zone during 2003 was estimated as 508,000 bbl/day. This volume was based on annual reports by operators to the Minerals Management Service. It reflects the volume of produced water that is generated from each lease, not the volume that is discharged from each platform.

The mass loadings from offshore oil and gas discharges to the entire hypoxic zone were estimated by multiplying the 50-platform loadings by the ratio of total water generated to the 50-platform discharge volume. The produced water loadings for the entire hypoxic zone are summarized in Table 2. To provide regional context, Table 2 also includes estimated mass loadings delivered to the Gulf from the MRB during 1980-1996. The produced water loadings of total nitrogen and total phosphorus for the entire hypoxic zone are 15,061 and 109 lb/day, respectively, and are several orders of magnitude lower than those from the MRB. Produced water loadings of ammonia nitrogen are 7.4 percent of those from the MRB; however, ammonia nitrogen loadings from the MRB are only 2 percent of the total nitrogen loadings from the MRB.

Development of Model Scenarios

Approach.

The study approach involved conducting predictive simulations with the original Bierman, Justić and Scavia models using the estimated produced water loads developed by Veil et al. (5). All model coefficients, including those representing degradation, decay, recycle and settling were kept the same as in the original models. The produced water loads were organized for each model to be compatible with their conceptual frameworks, state variables, and spatial scales. All produced water loads were assumed to be constant in time. Scenarios were designed for each model that addressed loading uncertainties, settleability of suspended biochemical oxygen demand (BOD) and total organic carbon (TOC), and, for the Justić and Scavia models, different assumptions on delivery locations for the produced water loads.

Results for the Bierman and Justić models are presented in terms of bottom water dissolved oxygen concentrations. Results for the Scavia model are presented in terms of area of hypoxia. Results for each model correspond to the incremental impacts of produced water loads, relative to results from the original models which included only loads from the MRB. These incremental impacts are reported in terms of percent change and absolute change.

Spatial Scales.

The spatial scale of the assessment study is shown in Figure 3. The indicated hypoxic zone corresponds to the spatial area for which there is greater than a 25 percent frequency of occurrence of hypoxia (Figure 1). This is the operational definition of the hypoxic zone for the estimated produced water loads in Veil et al. (5). The indicated oil and gas lease blocks correspond to the lease blocks in Figure 2 that lie within this hypoxic zone.

The spatial domain of the Bierman model is represented by a 21-segment grid extending from the Mississippi River delta west to the Louisiana-Texas border, and from the shoreline seaward to the 30-60 m bathymetric contours. The 14 model grid cells shown in Figure 3 correspond to the surface water segments in the model. The spatial grid includes one vertical layer nearshore and two vertical layers offshore. The nearshore segments have an average depth of 5.6 m. The surface offshore segments are completely mixed in the vertical to a fixed pycnocline depth of 10 meters. The bottom offshore segments are completely mixed from 10 meters to the seabed. The depths of these bottom offshore segments range between 6.1 and 20.3 meters. All predictive simulations with the Bierman model involved apportionment of the total produced water loads into individual model segments, depending on lease block locations and discharge depths.

Unlike the Bierman model, the spatial domains of the Justić and Scavia models did not completely coincide with all of the lease block locations in the hypoxic zone. Assumptions were required for each of these models on delivery points for the produced water loads. The scale at the bottom of Figure 3 indicates 20 km intervals along the spine of the hypoxic zone. For one set of predictive simulations with the Scavia model, total produced water loads were split into separate delivery points at the Mississippi and Atchafalaya Rivers, the delivery points in the original application of the model. Produced water loads from lease blocks between the Mississippi and Atchafalaya Rivers were delivered at the Mississippi delta, and produced water loads from lease blocks west of the Atchafalaya River were delivered at the Atchafalaya River mouth. For another set of predictive simulations with the Scavia model, total produced water loads were apportioned to 23 delivery points at the indicated 20 km intervals, depending on lease block locations. This scenario is a more realistic representation of the actual delivery points for produced water loads within the framework of the Scavia model.

Figure 4 shows spatial detail in the vicinity of Station C6, the monitoring station used for calibration of the Justić model. For one set of predictive simulations with the Justić model, produced water loads from lease blocks between the Mississippi delta and Station C6 were assumed to be delivered at the Mississippi River, the delivery point in the original application of the model. For another set of predictive simulations, produced water loads from lease blocks located within a 10 x 10 km grid centered on Station C6 were assumed to be delivered at Station C6. This scenario represents potential impacts at Station C6 due to near-field produced water loads. In contrast to the Bierman and Scavia models, which were both run with the total produced water loads, these two scenarios with the Justić model were run with only 47 and 8 percent, respectively, of the total produced water loads.

Assumptions.

In addition to the above assumptions on delivery points for produced water loads, the following additional assumptions were made for each of the three models:

- All of the produced water generated from each lease block is actually discharged.
- All produced water loads were assumed to be constant in time.
- Ultimate BOD (BOD_U) is equal to 1.25 times reported five-day BOD (BOD_5).
- The "suspended phase" fractions of BOD and TOC are 15 percent.
- Sixty-eight (68) percent of total produced water volume for the hypoxic zone is discharged to surface waters (0-10 meters) and 32 percent is discharged to bottom waters (below 10 meters).

The assumption that all produced water generated is actually discharged is consistent with Veil et al. (5). Produced water loads in Veil et al. (5) correspond only to current conditions. These loads were developed using chemical concentrations measured in 2005 and produced water volume generated in 2003. There are insufficient data to develop produced water loads for earlier historical conditions. Consequently, produced water loads were assumed to be constant in time for all of the predictive simulations in this study.

The assumptions for BOD_U and the "suspended phase" fractions of BOD and TOC were based on information provided by the industry work group (13). The assumed split between surface and bottom water discharges was developed using the OOC Hypoxia Registry database. The MMS Database on Produced Water Production by Lease during 2003 contains water production volumes but no information on discharge depths. The OOC Hypoxia Registry database has information on discharge depths, but does not correlate directly with the MMS database. Consequently, the assumed split between surface and bottom water discharges is an estimate using the best available data.

In the three original models it is assumed that the particulate phase fractions of BOD and TOC are settleable. If significant portions of the reported "suspended phase" BOD or TOC from produced waters are dispersed or colloidal oil droplets, then the settling characteristics of these "suspended phases" would be uncertain. To address this uncertainty, bounding simulations were conducted for these "suspended phase" produced water loads. As discussed above, the "suspended phase" was assumed to be 15 percent of the total reported produced water loads for both BOD and TOC. One bounding simulation assumed 100 percent settleability of this "suspended phase" and the other bounding simulation assumed zero settling of this phase.

Finally, to address uncertainties in produced water loads, bounding simulations were conducted at upper and lower 95 percent confidence intervals for each loading constituent.

These confidence intervals were provided by the industry work group (14). For each scenario and model, simulations were conducted with the following produced water loads:

- Base loads as reported in Veil et al. (5).
- Lower bound loads = Base loads – 95% confidence interval for each constituent.
- Upper bound loads = Base loads + 95% confidence interval for each constituent.

Bierman Model Scenarios.

A total of 18 predictive simulations were conducted with the Bierman model. For all simulations produced water (PW) loads were apportioned into individual model spatial segments, depending on lease block locations and discharge depths. Simulations were conducted for two settleability conditions:

- "Suspended phase" PW BOD settles.
- "Suspended phase" PW BOD does not settle.

Each of these settleability conditions included simulations with base, lower bound and upper bound PW loads and summer average, steady-state conditions for 1985, 1988 and 1990.

Justić Model Scenarios.

A total of 9 predictive simulations were conducted with the Justić model. Simulations were conducted for two PW delivery locations:

- Mississippi Delta - PW loads (nitrate nitrogen) only from lease blocks between the Mississippi delta and Station C6. These loads represent 47 percent of the total PW loads to the hypoxic zone.
- 10 x 10 km grid centered on Station C6 - PW loads (nitrate nitrogen and TOC) only from lease blocks within this grid. These loads represent 8 percent of the total PW loads to the hypoxic zone.

Simulations were conducted for two settleability conditions:

- "Suspended phase" PW TOC settles (only for 10 x 10 km grid).
- "Suspended phase" PW TOC does not settle (only for 10 x 10 km grid).

Simulations for each delivery location and settleability condition were conducted with base, lower bound and upper bound PW loads and results were developed for monthly average bottom water dissolved oxygen concentrations from 1955-2001.

The original application of the Justić model assumed that all nitrate nitrogen loads were delivered at the Mississippi delta and the resulting net primary productivity in the surface waters created vertical carbon flux to the bottom waters. The original application did not include any representation of riverine TOC loads. Consequently, "suspended phase" TOC is not represented in the predictive simulations with the Justić model that assumed delivery of PW loads at the Mississippi delta.

The Justić model predictive simulations that assumed delivery of PW loads from lease blocks within the 10 x 10 km grid did include explicit representation of TOC. The rationale was that PW loads of TOC from within this grid would affect vertical carbon flux to the bottom waters, and hence dissolved oxygen concentrations at Station C6. Consequently, the two settling conditions for "suspended phase" TOC were included in the Justić model predictions for PW loads delivered within the 10 x 10 km grid.

Scavia Model Scenarios.

A total of 12 predictive simulations were conducted with the Scavia model. Simulations were conducted for two PW delivery locations:

- Total PW loads split into delivery points at the Mississippi and Atchafalaya Rivers.
- Total PW loads apportioned to 23 delivery points at 20 km intervals along the spine of the hypoxic zone.

Simulations were conducted for two settleability conditions:

- Suspended phase" PW BOD settles from surface to bottom waters.
- "Suspended phase" PW BOD does not settle from surface to bottom waters.

Simulations for each delivery location and settleability condition were conducted with base, lower bound and upper bound PW loads and results are presented for summer average areal extent of hypoxia from 1985-2002.

The original application of the Scavia model assumed that total nitrogen load can be used as a surrogate for the organic matter load delivered to the bottom waters. Consistent with the approach used in the original application, PW loads of inorganic nitrogen to the surface waters were converted to settleable BOD in the form of algal cells, and then 50 percent of this algal BOD sinks below the pycnocline. In addition, it was assumed that PW loads of BOD (converted to BOD_U) delivered directly to the bottom waters also contributed to oxygen consumption.

Results

Bierman Model.

Table 3 contains predicted average percent changes in bottom water DO concentrations from the Bierman model for all scenarios. Each result corresponds to summer average, steady-state conditions, operationally defined as those occurring during July-August, the period during which annual hypoxia cruises are conducted by Dr. Nancy Rabalais and co-workers. Spatially, each result corresponds to the average percent change for the seven bottom water spatial segments in the model. As discussed below, these percent changes in bottom water DO concentrations are not constant in space, but vary over these seven spatial segments along the shelf contour. For base PW loads, results range from -0.110 to -0.201 percent for settling PW BOD and from -0.118 to -0.143 percent for non-settling PW BOD. The largest range across all of the lower- and upper-bound predictive simulations was from -0.091 to -0.237 percent.

Figures 5 and 6 show predicted percent changes in bottom water DO concentrations from the Bierman model for 1985 and 1990, respectively, for individual model spatial segments along the shelf contour. The spatial patterns for 1988 (7) are similar to those for 1985 and are not shown in this paper. Results are included for base, lower bound and upper bound PW loads, and for settling and non-settling PW BOD. For 1985 (Figure 5) the impacts of PW loads increase with distance from the delta and level off west of the Atchafalaya River, which is located 220 km downstream. There is little difference between results for settling and non-settling PW BOD near the delta, but impacts for non-settling PW BOD become greater west of the Atchafalaya. For 1990 (Figure 6) the results show different spatial patterns than for 1985, and there are greater differences between results for settling and non-settling PW BOD. Predicted impacts for non-settling PW BOD increase with distance from the delta, but more sharply than those for 1985. Predicted impacts for settling PW BOD are greater than those for non-settling PW BOD near the delta, but cross over and become smaller west of the Atchafalaya.

The predicted changes in actual bottom water DO concentrations due to PW loads are small and are not shown in this paper. The maximum predicted changes for base PW loads were approximately 0.010 mg/L for 1985 and 1988, and 0.012 mg/L for 1990.

Justić Model.

In the original predictions from the Justić model, bottom waters went hypoxic in 19 of 45 years from 1955 to 2000. In this study, there were no changes in frequency of hypoxia for any of the predictive simulations with PW loads. Bottom waters still went hypoxic in 19 of 45 years for all simulations. Furthermore, there were no changes in the number of months in which the bottom waters went hypoxic between the original predictions and the predictive simulations in this study.

Table 4 contains predicted average percent changes in bottom water DO concentrations from the Justić model for all scenarios. Each result corresponds to the average July-August percent change in bottom water DO concentrations at Station C6 from 1955 to 2001. For base PW loads delivered at the delta the average change was -0.0023 percent. For base PW loads delivered at the 10 x 10 km grid, the average change was -0.067 percent for non-settling PW TOC and -0.513 percent for settling PW TOC. The largest range across all of the lower- and upper-bound predictive simulations was from -0.0017 to -0.660 percent.

Produced Water (PW) Loads Delivered at Mississippi Delta.

Figure 7 shows predicted percent changes in monthly bottom water DO concentrations from the Justić model at Station C6 for 1985-2001. Predictions were also made for 1955-1984 (7) but results are not shown in this paper. Results in Figure 7 are included for base, lower bound and upper bound PW loads. The greatest predicted impacts occur in summer of each year. The maximum predicted impact of base PW loads was approximately -0.016 percent for summer 1990. The maximum predicted impact of base PW loads on actual DO concentrations during 1985-2001 is not shown, but was approximately -0.0002 mg/L in the summers of 1990 and 1997.

Produced Water (PW) Loads Delivered at 10 x 10 Km Grid.

Figure 8 shows predicted percent changes in monthly bottom water DO concentrations from the Justić model at Station C6 for 1985-2001. Predictions were also made for 1955-1984 (7) but results are not shown in this paper. Results in Figure 8 are included for base, lower bound and upper bound PW loads. The greatest predicted impacts occur in summer of each year. The maximum predicted impact of base PW loads during 1985-2001 was approximately -1.3 percent for summer 1995. Impacts are substantially greater for settling PW TOC than for non-settling PW TOC, and they are outside the ranges of the PW loading uncertainties.

The maximum predicted impact of base PW loads on actual DO concentrations during 1985-2001 is not shown, but was approximately -0.03 mg/L in summer 1987. Impacts are substantially greater for settling PW TOC than for non-settling PW TOC, and they are outside the ranges of the PW loading uncertainties.

Scavia Model.

Produced Water (PW) Loads Delivered at Mississippi and Atchafalaya Rivers.

Figure 9 shows predicted percent changes in hypoxic area from the Scavia model for 1985-2002. For base PW loads the hypoxic area increased in 3 of 18 years (1986, 1987 and 1998). The average increase was 4.5 percent and there were no differences between the settling and non-settling PW BOD cases. Predicted results for lower bound PW loads were the same as those for base PW loads. For upper bound PW loads the hypoxic area increased in 4 of 18 years (1986, 1987, 1991 and 1998). The average increase was 4.1 percent and there were no differences between the settling and non-settling PW BOD cases. The predicted increase in actual hypoxic area for all four of these impacted years is not shown but was 331 km^2 (9).

Produced Water Loads Delivered Along Spine of Hypoxic Zone.

Figure 10 shows predicted percent changes in hypoxic area for 1985-2002. For base PW loads the hypoxic area increased in 2 of 18 years (1986 and 1991). The average increase was 3.1 percent and there were no differences between the settling and non-settling PW BOD cases. Predicted results for lower bound PW loads were the same as those for base PW loads.

For upper bound PW loads the hypoxic area increased in 3 of 18 years (1986, 1991 and 1995) for settling PW BOD and in 2 of 18 years (1986, 1991) for non-settling PW BOD. The average increases were 2.8 and 3.1 percent, respectively, for these two cases. The predicted increase in actual hypoxic area for all three of these impacted years is not shown but was 331 km^2 (7).

Discussion

The PW loads used in this study correspond only to current conditions and were assumed to be constant in time for all of the predictive simulations conducted. These simulations involved the following time periods for each of the three models: Bierman (1985, 1988, 1990), Justić (1955-2001) and Scavia (1985-2002). It should be noted that predicted impacts of PW loads for periods of time earlier than current conditions do not necessarily represent the impacts of actual PW loads during these periods.

The predictions from the Bierman model appear consistent with the relative contribution of PW loads to the northern Gulf of Mexico. Produced water loads contributed 0.16 percent of the total nitrogen loading to the northern Gulf (Table 2). For base PW loads, predicted impacts on average summer bottom water DO concentrations ranged from -0.110 to -0.201 percent for settling PW BOD and from -0.118 to -0.143 percent for non-settling PW BOD (Table 3).

The predictions from the Justić model appear consistent with the relative contribution of PW nitrate nitrogen loads to the northern Gulf of Mexico. Produced water loads contributed 0.003 percent of the total nitrate nitrogen loading to the northern Gulf (Table 2). For base PW loads delivered at the Mississippi delta, the predicted impact on average summer bottom water DO concentrations was -0.0023 percent. It is not possible to evaluate the predictions from the Justić model for PW loads delivered at the 10 x 10 km grid in the same context because this scenario represents predicted impacts due only to near-field PW loads from lease blocks within this grid.

The predictions from the Scavia model represent area of summer hypoxia and can not be related to the relative contributions of PW loads in the same way as predictions from the Bierman and Justić models for bottom water DO concentrations. For base PW loads delivered at the Mississippi and Atchafalaya Rivers, the average predicted impact on hypoxic area was +4.5 percent; however, impacts were predicted to occur in only 3 of 18 years (1986, 1987 and 1998) and this average represents the predicted impacts in those three years. There were no predicted increases in hypoxic area for the other 15 years. For base PW loads delivered along the spine of the hypoxic zone, the averaged predicted impact on hypoxic area was +3.1 percent; however, impacts were predicted to occur in only 2 of 18 years (1986 and 1991) and this average represents the predicted impacts in those two years.

For 1990 (Figure 6) predicted results from the Bierman model show different spatial patterns than for 1985 (Figure 5) and 1988 (7), and there are greater differences between results for settling and non-settling PW BOD. These predicted differences are due to differences in the structure of the water circulation field on the Louisiana-Texas shelf (15). Water circulation on the shelf is strongly influenced by wind stress and freshwater discharges from the MRB. It is believed that summer average conditions on the shelf are typically represented by the Louisiana Coastal Current which has a net westward drift along the shelf contour. This representation is supported by current meter measurements from a long-term mooring maintained by W.J. Wiseman, Jr., formerly of Louisiana State University, at Station C6 in 20 meters of water. Typical summer average current speeds are approximately 10 and 3 cm/sec, respectively, in the surface and bottom waters.

In summer 1990 water circulation on the shelf deviated from these typical conditions and altered computed water quality responses. Net eastward drift was observed in both surface and bottom waters, and at lower speeds of approximately 2 and 0.8 cm/sec, respectively. A consequence was longer effective hydraulic detention times in each of the model spatial segments, and hence longer periods of time for degradation of organic carbon in the water column and contact between oxygen-demanding sediments and bottom waters. This interplay between altered physics and chemical-biological processes influenced the magnitude and spatial distribution of computed dissolved oxygen concentrations in bottom waters along the shelf contour.

Predictions from the Bierman model show that impacts for non-settling PW BOD are greater than those for settling PW BOD in the region west of the Atchafalaya for all three years. This appears to be counterintuitive, but stems from the fact that there are two vertical settling fluxes for BOD in the Bierman model: 1. settling from surface to bottom waters; and 2. settling from bottom waters to the sediment bed. The settling case has greater flux of suspended phase PW BOD from surface to bottom waters than the non-settling case; however, it also has loss of suspended phase PW BOD from the bottom waters to the sediment bed. Conversely, the non-settling case has less vertical flux of suspended phase PW BOD from surface to bottom waters; however it has no loss of suspended phase PW BOD from the bottom waters to the sediment bed. The primary driver for consumption of bottom water DO is bottom water BOD. Depending on circulation, bathymetry and location along the shelf contour, decreased vertical flux of BOD from surface to bottom waters (a BOD source) can be offset by decreased vertical flux of BOD from bottom waters to the sediment bed (a BOD sink).

All of the predictive results in this study contain uncertainties inherent in each of the original models, in addition to the uncertainties explicitly considered for the produced water loads. Despite uncertainties in model results for absolute magnitudes of dissolved oxygen concentrations and hypoxic areas, relative differences between baseline and predictive simulations have higher degrees of confidence because the absolute uncertainties tend to be self-cancelling.

Conclusions

The predicted incremental impacts of produced water loads on dissolved oxygen conditions in the northern Gulf of Mexico from all three models were small. Even considering the predicted ranges between lower- and upper-bound results, these impacts are likely to be within the errors of measurement for bottom water dissolved oxygen and hypoxic area at the spatial scale of the entire hypoxic zone.

Nomenclature

BOD = biochemical oxygen demand, m/L^3, mg/liter
BOD_5 = five-day BOD, m/L^3, mg/liter
BOD_U = ultimate BOD, m/L^3, mg/liter
bbl/day = barrels per day, V/t, bbl/day
DO = dissolved oxygen concentration, m/L^3, mg/liter
DOE = Department of Energy
EPA = U.S. Environmental Protection Agency
lbs/day = pounds per day, m/t, lbs/day
MMS = Minerals Management Service
MRB = Mississippi River Basin
NPDES = National Pollutant Discharge Elimination System
OOC = Offshore Operators Committee
PW = produced water, dimensionless
TOC = total organic carbon concentration, m/L^3, mg/liter

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References

1. Committee on Environment and Natural Resources (CENR). 2000. Integrated Assessment of Hypoxia in the Northern Gulf of Mexico. National Science and Technology Council, Washington, D.C.

2. U.S. Environmental Protection Agency. 2001. Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico, Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, EPA841-F-01-001, Washington, DC.

3. Rabalais, N.N, R.E. Turner, and D. Scavia. 2002. Beyond science into policy: Gulf of Mexico Hypoxia and the Mississippi River. BioScience 52: 129-142.

4. Goolsby, D.A., W.A. Battaglin, B.T. Aulenbach, and R.P. Hooper. 2001. Nitrogen input to the Gulf of Mexico. J. Environ. Qual. 30: 329-336.

5. Veil, J.A., T.A. Kimmell and A.C. Rechner. 2005. Characteristics of Produced Water Discharged to the Gulf of Mexico Hypoxic Zone. Prepared for U.S. Department of Energy, National Energy Technology Laboratory, Contract W-31-109-Eng-38, Argonne National Laboratory.

6. Scavia, D., D. Justić and V.J. Bierman, Jr. 2004. Estuaries 27: 419-425.

7. Limno-Tech, Inc. 2006. Predicted Impacts from Offshore Produced Water Discharges on Hypoxia in the Gulf of Mexico. Prepared for U.S. Environmental Protection Agency, Region 6, Dallas, TX, through Battelle, Duxbury, MA. EPA Contract No. 68-C-03-041.

8. Bierman, V.J., Jr., S.C. Hinz, D. Zhu, W.J. Wiseman, Jr., N.N. Rabalais, and R.E. Turner. 1994. A preliminary mass balance model of primary productivity and dissolved oxygen in the Mississippi River plume/inner Gulf Shelf region. Estuaries 17: 886–99.

9. Justić, D., N. N. Rabalais, and R. E. Turner. 1996. Effects of climate change on hypoxia in coastal waters: a doubled CO_2 scenario for the northern Gulf of Mexico. Limnol. Oceanogr. 41: 992-1003.

10. Justić, D., N. N. Rabalais, and R. E. Turner. 2002. Modeling the impacts of decadal changes in riverine nutrient fluxes on coastal eutrophication near the Mississippi River Delta. Ecological Modelling 152: 33-46.

11. Scavia, D., N.N. Rabalais, R. E. Turner, D. Justić, and W. J. Wiseman, Jr. 2003. Predicting the response of Gulf of Mexico hypoxia to variations in Mississippi River nitrogen load. Limnol. Oceanogr. 48: 951-956.

12. Parker, M.E., K. Satterlee and J.A. Veil. 2006. Impacts from oil and gas produced water discharges on the Gulf of Mexico hypoxic zone. Presentation at the SPE International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production, Abu Dhabi, U.A.E., April 2-4, 2006.

13. Veil, J.A. 2006a. Questions from Vic Bierman to John Veil (2/28/06) and Veil's Answers (3/1/06). Technical Memorandum, March 8, 2006.

14. Veil, J.A. 2006b. Recommended Upper and Lower Range Values for Hypoxic Zone Sensitivity Analysis. Technical Memorandum, February 12, 2006.

15. Limno-Tech, Inc. 1995. Estimated responses of water quality on the Louisiana Inner Shelf to nutrient load reductions in the Mississippi and Atchafalaya Rivers. Unnumbered report. Stennis Space Center, MS: U.S. Environmental Protection Agency, Gulf of Mexico Program.

16. Goolsby, D.A., W.A. Battaglin, G.B. Lawrence, R.S. Artz, B.T. Aulenbach, R.P. Hooper, D.R. Keeney and G.J. Stensland. 1999. Flux and Sources of Nutrients in the Mississippi-Atchafalaya River Basin: Topic 3 Report for the Integrated Assessment on Hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Series No. 17. NOAA Coastal Ocean Program, Silver Spring, MD. 130 pp.

Table 1. Principal Attributes of Gulf of Mexico Hypoxia Models

Attribute	MODEL		
	Bierman	Justić	Scavia
General Description	Moderately complex mechanistic eutrophication model	Simple two-layer dissolved oxygen model	Simple dissolved oxygen model for bottom waters
Spatial Scale	3D with 21 spatial segments in hypoxic zone	1D vertical at Station C6 in core of hypoxic zone	1D horizontal in subpycnocline downstream of river inputs
Temporal Scale	Summer Steady-State	Monthly Time-Variable	Summer Steady-State
Nutrients	Phosphorus, nitrogen and silicon	Nitrogen	Nitrogen
Hypoxia Characterization	3D structure of summer-average dissolved oxygen concentrations in hypoxic zone	Seasonal dynamics of dissolved oxygen concentrations in core of hypoxic zone	Interannual variability in hypoxic zone length and area
Calibration Time Periods	1985, 1988 and 1990	1985-1993	1985-2002

Table 2. Relative Contributions of Loadings from Produced Waters

Parameter	Mean Daily Loads from MRB to Gulf of Mexico, 1980-1996* (lbs/day)	Estimated Mean Daily Loads from Produced Waters to Gulf of Mexico Hypoxic Zone** (lbs/day)	Percent Contributions of Produced Waters
Total N	9,470,000	15,061	0.16
Nitrate N	5,750,000	197	0.003
Ammonia N	187,000	13,804	7.38
Total P	824,000	109	0.013
Orthophosphate P	252,000	65	0.026

*adapted from 16
**adapted from 5

Table 3. Predicted Average Percent Changes in Summer Bottom Water Dissolved Oxygen Concentrations from the Bierman Model.

	Produced Water (PW) Loads		
Scenario	**Base**	**Lower Bound**	**Upper Bound**
1985			
Suspended PW BOD Settles	-0.110	-0.091	-0.130
Suspended PW BOD Does Not Settle	-0.118	-0.099	-0.138
1988			
Suspended PW BOD Settles	-0.118	-0.097	-0.139
Suspended PW BOD Does Not Settle	-0.138	-0.117	-0.159
1990			
Suspended PW BOD Settles	-0.201	-0.165	-0.237
Suspended PW BOD Does Not Settle	-0.143	-0.107	-0.179

Table 4. Predicted Average Percent Changes in Summer Bottom Water Dissolved Oxygen Concentrations from the Justić Model.

	Produced Water (PW) Loads		
Scenario	**Base**	**Lower Bound**	**Upper Bound**
PW Loads (Nitrate Nitrogen) Delivered at Mississippi Delta			
Suspended PW TOC Settles	-0.0023	-0.0017	-0.0031
Suspended PW TOC Does Not Settle	N/A	N/A	N/A
PW Loads (Nitrate Nitrogen and TOC) Delivered at 10 x 10 Km Grid Centered on Station C6			
Suspended PW TOC Settles	-0.513	-0.368	-0.660
Suspended PW TOC Does Not Settle	-0.067	-0.049	-0.087

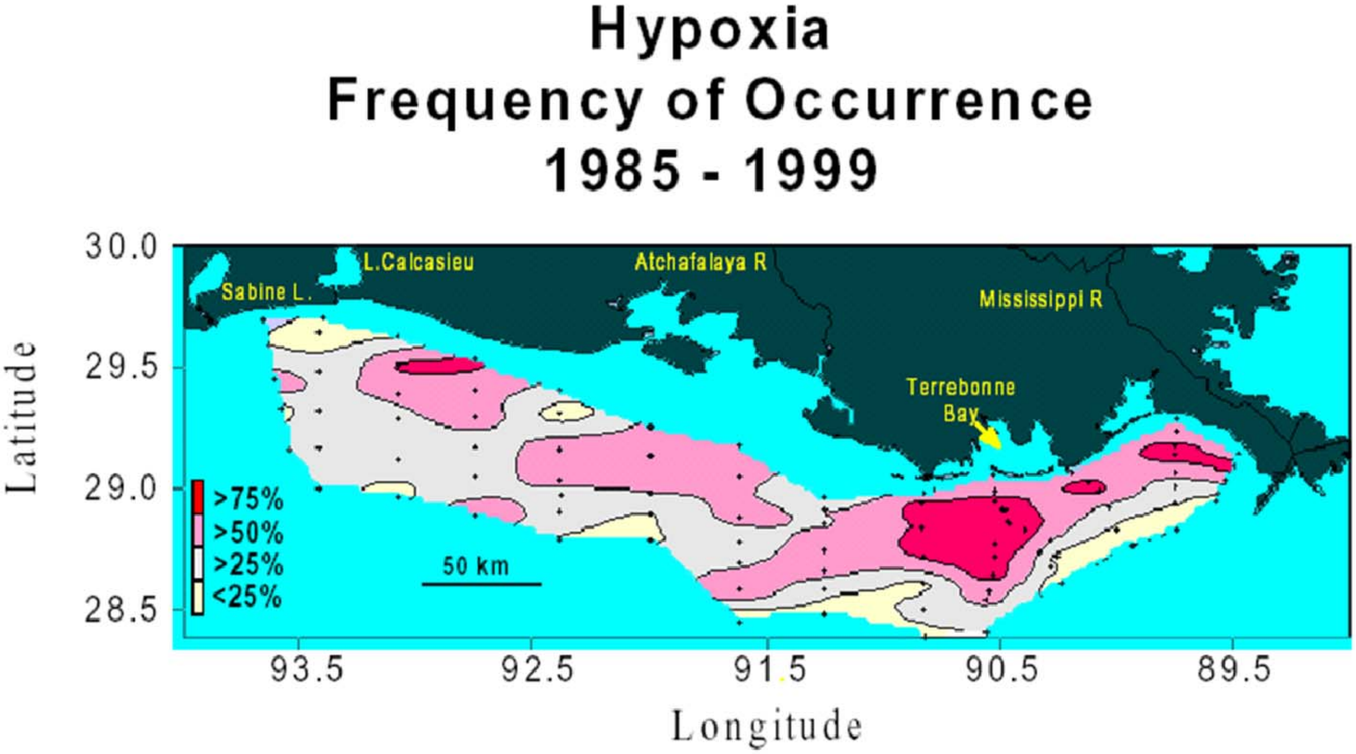

Figure 1. Frequency of occurrence of mid-summer hypoxia in the Gulf of Mexico – based on data from Rabalais, Turner and Wiseman (1).

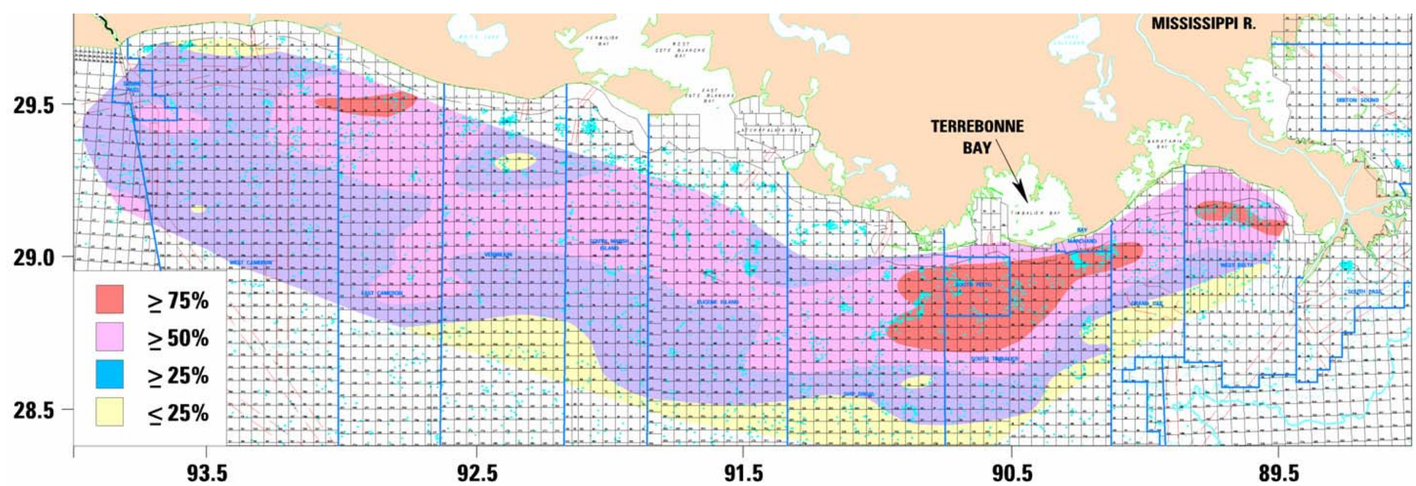

Figure 2. Map of hypoxic zone showing numbers and locations of oil and gas platforms.

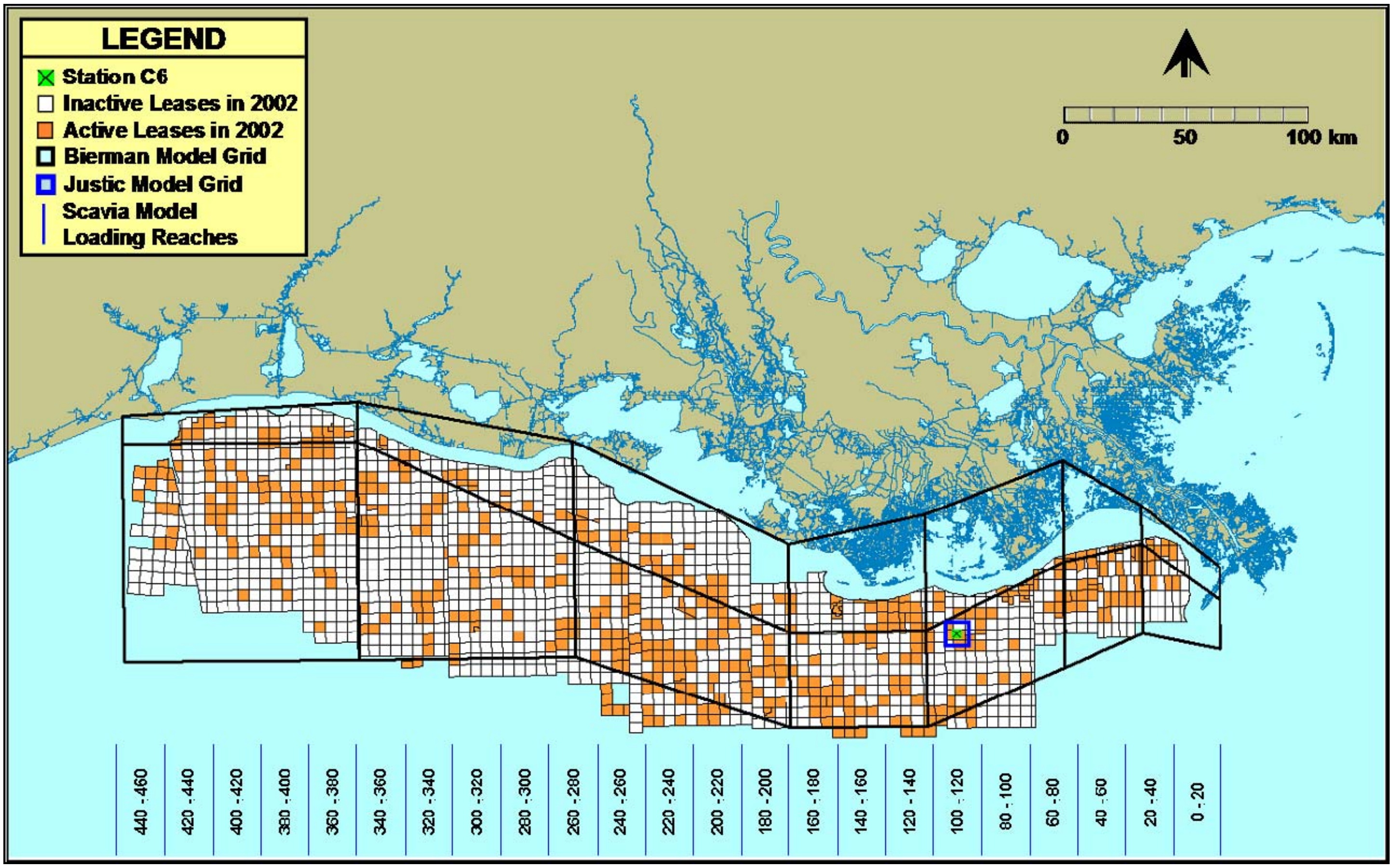

Figure 3. Hypoxic zone on the Louisiana-Texas Shelf showing oil and gas lease blocks, locations of Bierman model grid cells, Station C6 for the Justić model, and loading intervals along the spine of the hypoxic zone for the Scavia model.

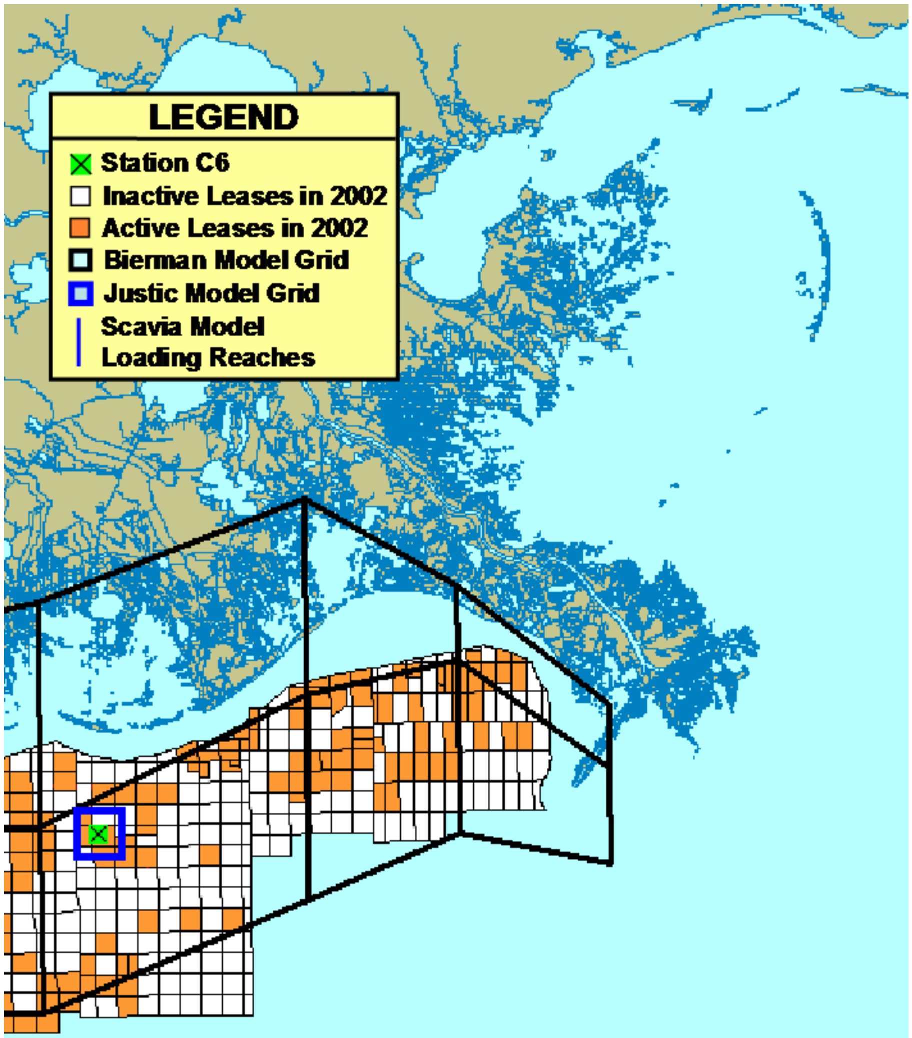

Figure 4. Spatial detail in the vicinity of Station C6 for the Justić model.

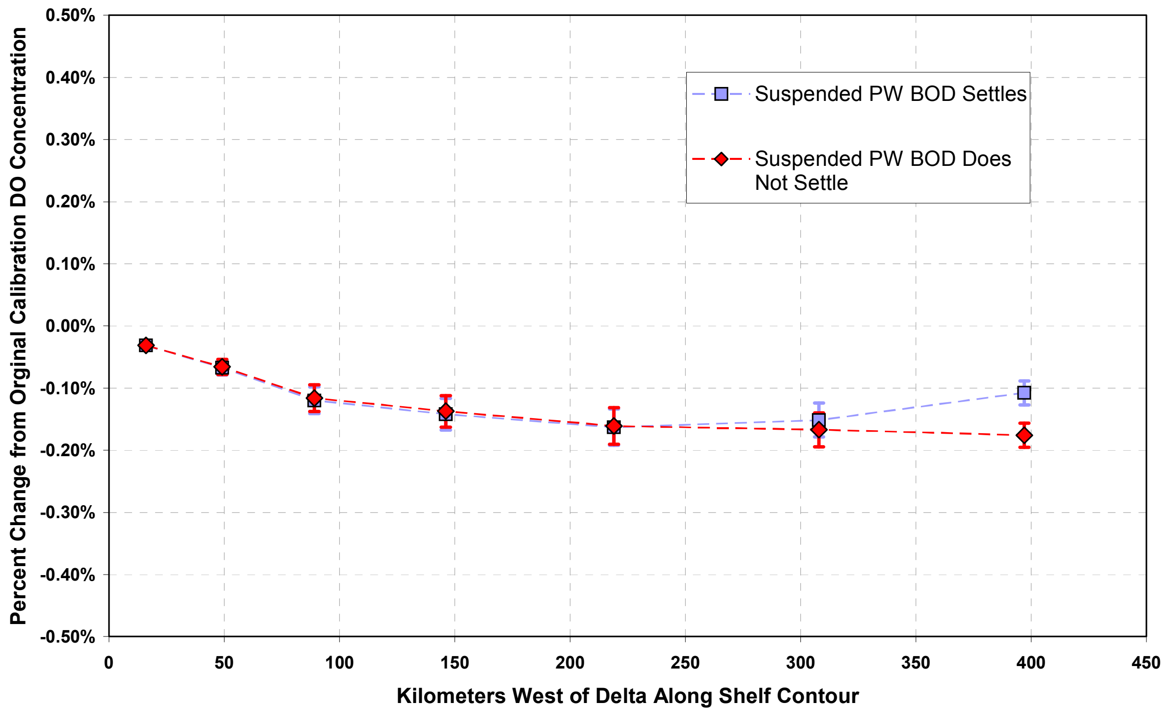

Figure 5. Predicted percent changes in bottom water dissolved oxygen concentrations for summer 1985 due to produced water loads. Results shown for base, lower bound and upper bound loads for each BOD settling case.

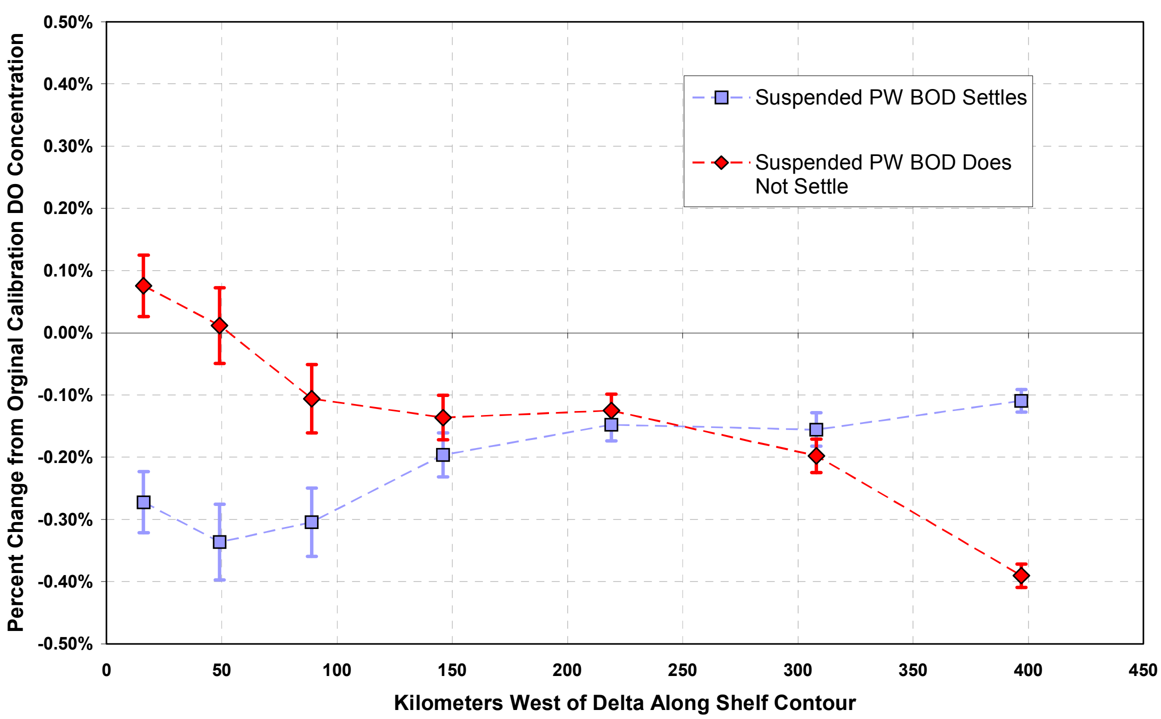

Figure 6. Predicted percent changes in bottom water dissolved oxygen concentrations for summer 1990 due to produced water loads. Results shown for base, lower bound and upper bound loads for each BOD settling case.

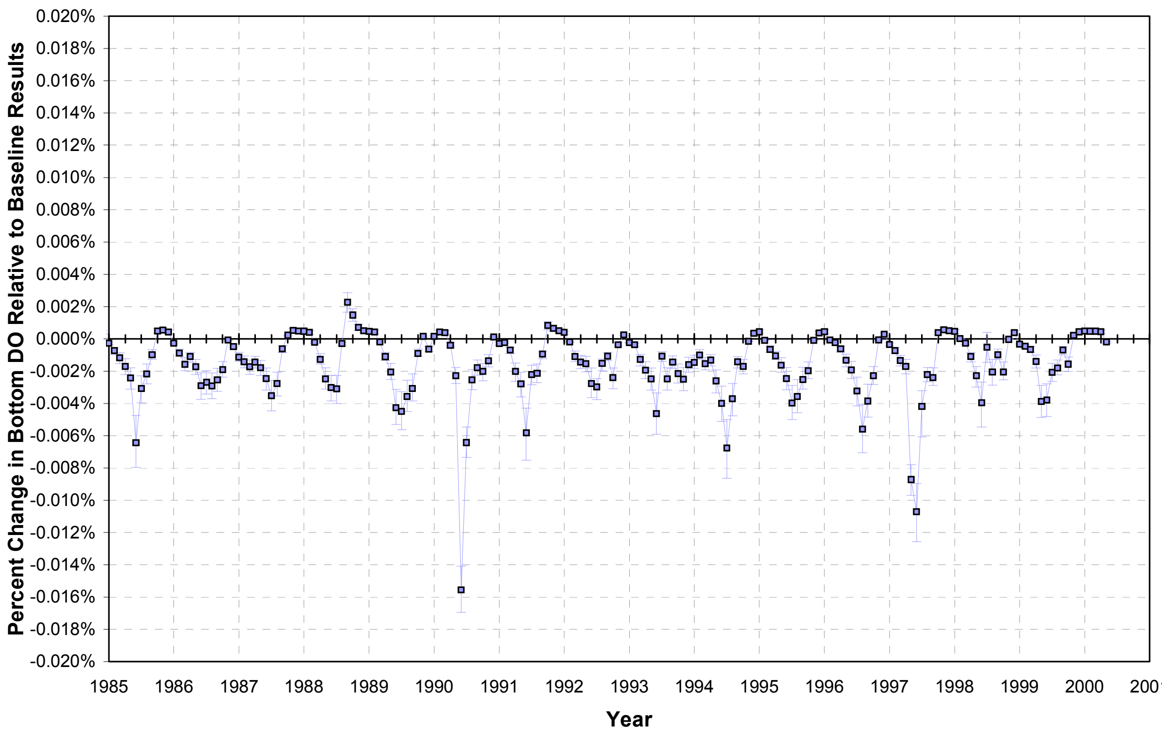

Figure 7. Predicted percent changes in monthly bottom water dissolved oxygen concentrations at Station C6 during 1985-2001 due to produced water loads (nitrate nitrogen) delivered at the Mississippi Delta. Results shown for base, lower bound and upper bound loads.

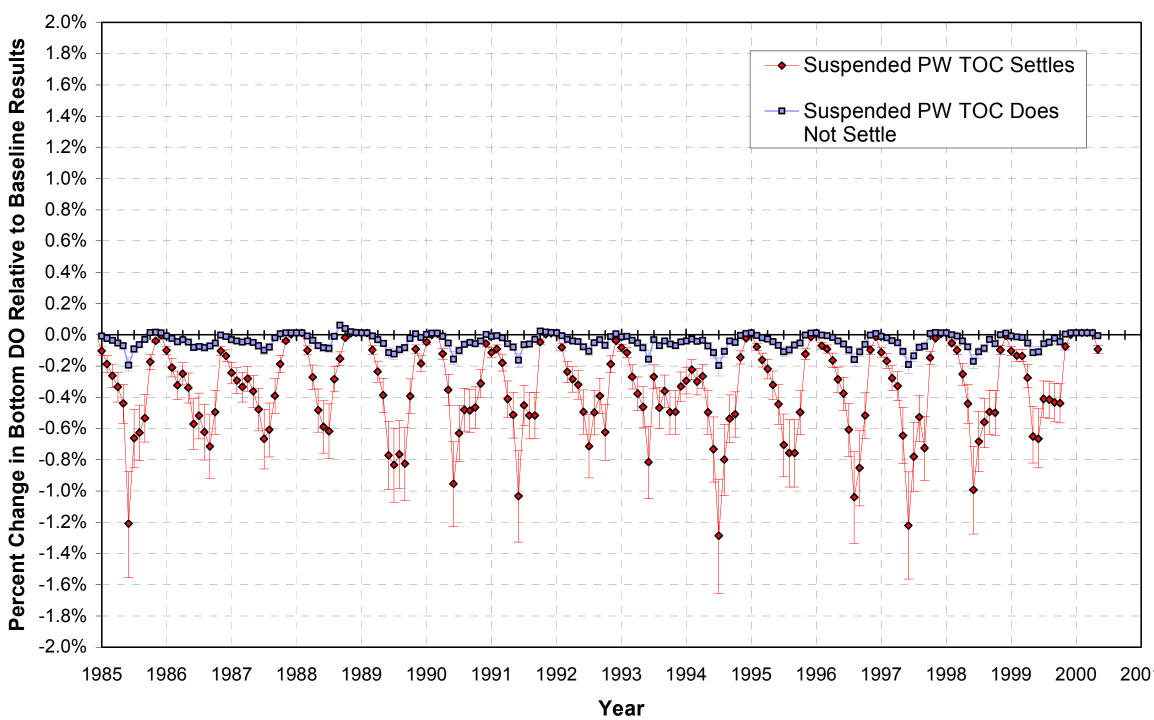

Figure 8. Predicted percent changes in monthly bottom water dissolved oxygen concentrations at Station C6 during 1985-2001 due to produced water loads (nitrate nitrogen and TOC) delivered at the 10x10 km grid. Results shown for base, lower bound and upper bound loads for each TOC settling case.

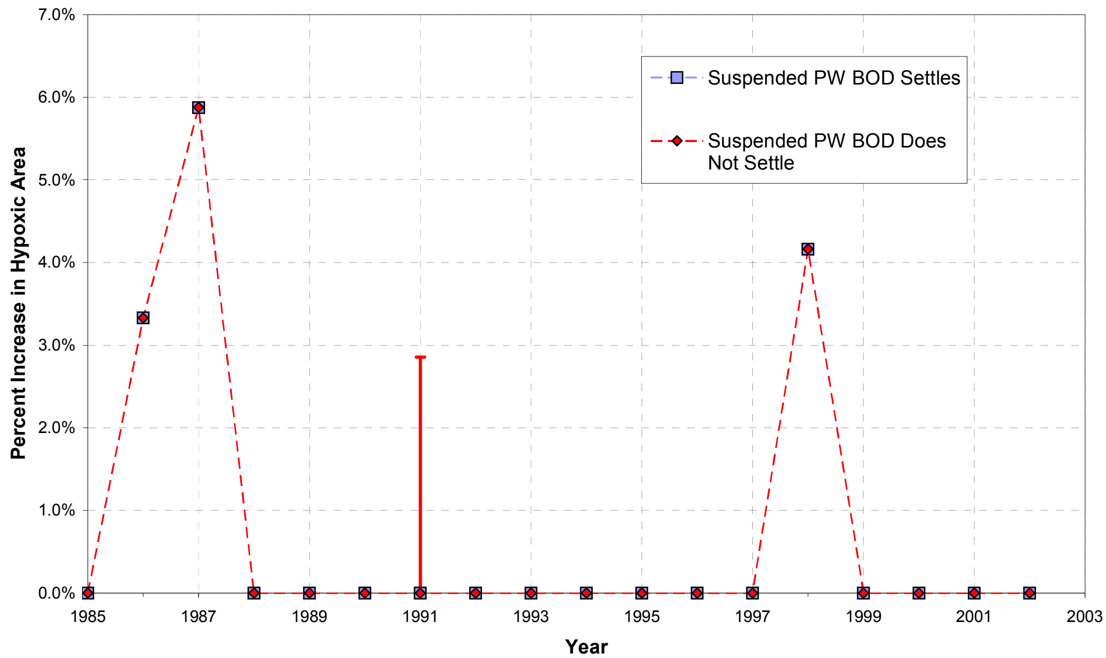

Figure 9. Predicted percent changes in hypoxic area due to produced water loads delivered at the Mississippi and Atchafalaya Rivers. Results shown for base, lower bound and upper bound loads for each BOD settling case.

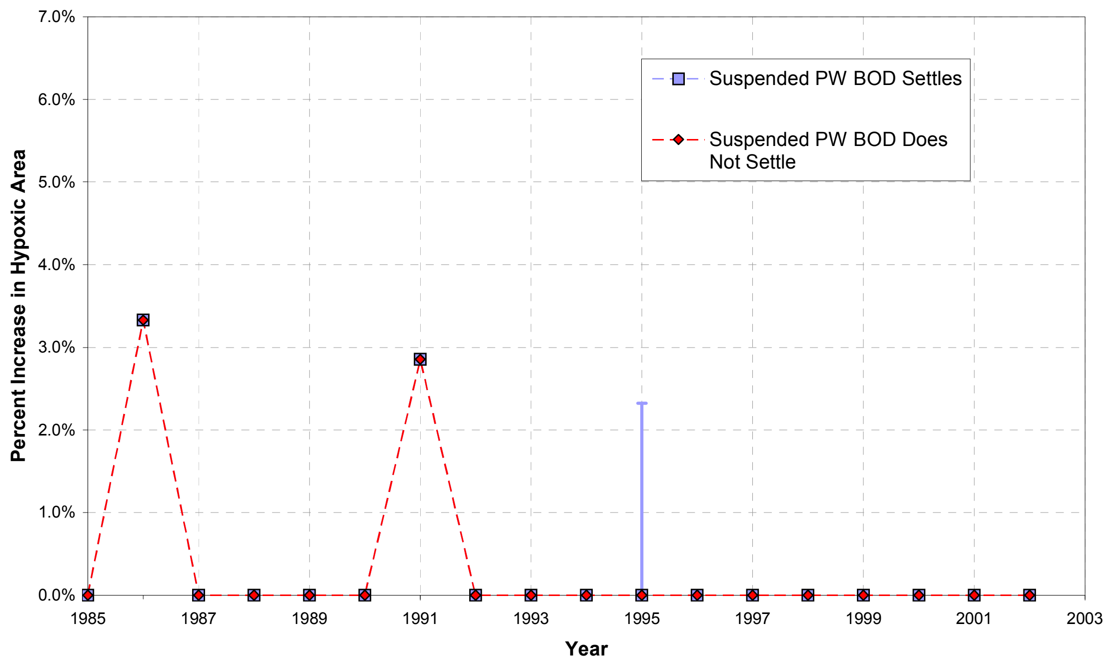

Figure 10. Predicted percent changes in hypoxic area due to produced water loads delivered at 20 km intervals along the spine of the hypoxic zone. Results shown for base, lower bound and upper bound loads for each BOD settling case.