Hypoxia in the Gulf of Mexico*

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I. DIMENSIONS OF GULF OF MEXICO HYPOXIA

The largest zone of oxygen-depleted coastal waters in the United States, and the entire western Atlantic Ocean, is found in the northern Gulf of Mexico on the Louisiana and Texas continental shelf, influenced by the freshwater and nutrient flux of the Mississippi River system.[1] Hypoxia covers broad regions of the shelf for extended periods in mid-summer.[2] The mid-summer extent of hypoxic waters[3] between 1985 and 1992 averaged 8,000 to 9,000 km^2 but increased to between 16,000 and 18,000 km^2 from 1993 to 1997.[4] The prevailing

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1. *See* Nancy N. Rabalais et al., *Nutrient Changes in the Mississippi River and System Responses on the Adjacent Continental Shelf*, 19 ESTUARIES 386, 386-87 (1996) [hereinafter Rabalais et al., *Nutrient Changes in the Mississippi River*].
2. *See* Nancy N. Rabalais et al., *Consequences of the 1993 Mississippi River Flood in the Gulf of Mexico*, 14 REGULATED RIVERS: RES. & MGMT. 161, 161-62 (1998) [hereinafter Rabalais et al., *1993 Mississippi River Flood*].
3. Those waters with oxygen concentrations less than or equal to 2 mg/l or ppm. *Id.* at 162.
4. *See infra* Appendix 1; Rabalais et al., *1993 Mississippi River Flood*, *supra* note 2, at 175.

oceanographic conditions in 1998 reduced the hypoxic zone to 12,480 km^2.[5]

Low oxygen has been documented as early as February and as late as October, but is most widespread, persistent and severe from May to September in water depths of five to thirty meters.[6] Hypoxia occurs mostly in the lower water column but may encompass as much as the lower half to two-thirds of the total water column.[7] Continuous time-series data for the bottom waters in the core of the hypoxia region show (1) the gradual decline in oxygen in the spring with interruptions due to wind-mixing events,[8] (2) persistent and severe hypoxia and anoxia for extended parts of the record from May to October,[9] (3) occasional summer upwelling of oxygenated water from the outer shelf,[10] and (4) the seasonal disruption of low oxygen in the fall from tropical storms or cold fronts.[11]

The Mississippi River system encompasses forty one percent of the conterminous United States and delivers 580 km^3 of fresh water, 130.3 x 10^6 kg atoms of nitrogen, and 210 x 10^6 tons of sediment to the Gulf yearly.[12] Thus, the dimensions of the hypoxia problem and the size and complexity of the freshwater-to-marine ecosystem are of much greater proportion than most nutrient-driven eutrophication problems elsewhere in the world.

II. INTERACTION OF PHYSICS AND BIOLOGY IN THE DEVELOPMENT AND MAINTENANCE OF HYPOXIA

The physics of the coastal system and the biological processes that occur there are linked. For hypoxia to develop and be maintained, the water column must be stratified and there must be an excess of carbon exported from surface waters to the lower water column and seabed.[13] The high fresh water discharge in the Gulf of Mexico, the general circulation patterns of the Louisiana shelf, and the presence of the Louisiana coastal current dictate a stratified

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5. *See infra* Appendices 1-2; Rabalais et al., *1993 Mississippi River Flood*, *supra* note 2, at 175.
6. *See* Rabalais et al., *1993 Mississippi River Flood*, *supra* note 2, at 162.
7. *See id.*
8. *See* Rabalais et al., *Nutrient Changes in the Mississippi River*, *supra* note 1, at 388-89.
9. *See* Rabalais et al., *1993 Mississippi River Flood*, *supra* note 2, at 162.
10. *See* Rabalais et al., *Nutrient Changes in the Mississippi River*, *supra* note 1, at 388-89.
11. *See id.* at 389.
12. *See id.* at 387.
13. *See id.* at 391.

system for much of the year.[14] This system is interrupted on occasion by wind-mixing events, notably tropical storms and winter cold fronts.[15] The best current knowledge is that the outflows of the Mississippi and Atchafalaya Rivers dominate the nutrient loads to the continental shelf where hypoxia is likely to develop.[16]

III. NUTRIENT-ENHANCED PRODUCTIVITY

The evidence for nutrient enhanced primary production in the northern Gulf of Mexico and its linkage with oxygen depletion in the lower water column comes from information on a variety of scales, from experiments on a parcel of water from a particular locale over a limited time to more integrative measures of ecosystem response (e.g., net production, carbon flux and respiration) and change over broader spatial and temporal scales.[17] The concentrations, total loads and ratios of nutrients (nitrogen, phosphorus and silica) delivered to the coastal ocean influence the productivity of the phytoplankton community as well as the types of phytoplankton that are most likely to grow.[18] The nutrient most relevant to overall phytoplankton production over the broad region fueling hypoxia is nitrogen (in its ratio to silicate),[19] and nitrate-N makes up approximately two-thirds of the total nitrogen input from the Mississippi River.[20] Silica and phosphorus may also be limiting at some times and places.[21] There is clear evidence that nutrient enhanced primary production in shelf waters near the Mississippi River delta, and to some distance from it, are significantly correlated with nutrient inputs (nitrate+nitrite and orthophosphate).[22] Similar relationships exist with net production[23] and nitrate flux.[24] There is also a strong relationship between the net production in surface waters, the amount of carbon exported, the accumulation rates of carbon, and the depletion of oxygen in bottom

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14. *See id.*
15. *See id.* at 388-89.
16. *See id.* at 387, 394.
17. *See id.* at 394.
18. *See id.* at 387.
19. *See id.* at 402.
20. *See* R. Eugene Turner & Nancy N. Rabalais, *Changes in Mississippi River Water Quality This Century*, 41 BIOSCIENCE 140, 143 (1991) [hereinafter Turner & Rabalais, *Mississippi River Water Quality*].
21. *See* Rabalais et al., *Nutrient Changes in the Mississippi River*, *supra* note 1, at 387.
22. *See id.* at 389.
23. Net production is an indicator of the amount of carbon available for export to the sediments.
24. *See* Rabalais et al., *Nutrient Changes in the Mississippi River*, *supra* note 1, at 389; Rabalais et al., *1993 Mississippi River Flood*, *supra* note 2, at 163.

waters.[25] Thus, there are clear lines of evidence that indicate nitrogen (particularly nitrate) driven phytoplankton production leads to hypoxia.

Enhanced phytoplankton productivity further enhances pelagic and demersal populations.[26] The enhancement of pelagic fisheries is demonstrated by the high tonnage landings of the Gulf menhaden fishery.[27] Shrimp, which constitute the most valuable Louisiana fishery resource, depend on the organic matter that ultimately sinks to the bottom and supports a benthic-based food web.[28] When the rate of organic supply and subsequent depletion of oxygen affects the survival of organisms and/or their ability to reside either at the bottom or within the water column, disruptions occur in benthic, demersal and pelagic communities.[29]

IV. LONG-TERM CHANGES IN THE MISSISSIPPI RIVER SYSTEM AND NORTHERN GULF OF MEXICO

It follows, and is supported with evidence from long-term data sets and the sedimentary record, that increases in riverine dissolved inorganic nitrogen loads are highly correlated with indicators of increased productivity in the overlying water column (i.e., eutrophication of the continental shelf waters) and subsequent worsening of oxygen stress in the bottom waters.[30] Human activities in the watershed have undoubtedly changed the natural functioning of the Mississippi River system and contributed to changes in the nutrient loads. Century-long patterns of freshwater discharge are not evident; thus, the changes on the Louisiana shelf are linked to the quality of the discharge (nutrients loads and ratios of nutrients) and not the amount.[31] The nitrogen and phosphorus loads of the Mississippi River system were unchanged from the turn of the century

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25. *See* Rabalais et al., *Nutrient Changes in the Mississippi River*, *supra* note 1, at 390-91.

26. *See* R. Eugene Turner & Nancy N. Rabalais, *Coastal Eutrophication Near the Mississippi River Delta*, 368 NATURE 619, 620-21 (1994) [hereinafter Turner & Rabalais, *Coastal Eutrophication*].

27. *See* Fisheries Statistics & Economics Div., Nat'l Oceanic and Atmospheric Admin., *Commercial Fisheries* (visited May 27, 1999) <http://www.st.nmfs.gov/st1/commercial/>.

28. *See* R.J. Zimmerman et al., *Trends in Shrimp Catch in the Hypoxic Area of the Northern Gulf of Mexico*, *in* NO. EPA-55-R-97-001, PROCEEDINGS OF THE FIRST GULF OF MEXICO HYPOXIA MANAGEMENT CONFERENCE 64, 64-75 (Gulf of Mexico Program, U.S. EPA, 1997).

29. *See* Rabalais et al., *1993 Mississippi River Flood*, *supra* note 2, at 175.

30. *See* Rabalais et al., *Nutrient Changes in the Mississippi River*, *supra* note 1, at 400-01.

31. *See id.*

to the early 1950s.[32] Nitrogen then doubled to a level that plateaued in the late 1980s.[33] Similarly, the amount of silicate[34] has decreased by half since the 1950s.[35]

Long-term data that would document the occurrence of hypoxia earlier than the 1970s do not exist. Sediment cores from the Mississippi River bight provide surrogates for historical conditions in overlying waters and the benthic habitat.[36] While century-long changes are evident in some of the retrospective analyses, the most dramatic and accelerating changes have occurred since the 1950s, when nitrogen loads began to increase and eventually doubled over their historic values.[37] Phytoplankton production, diatom production, and carbon from phytoplankton that accumulates in the sediments have increased since the 1950s.[38] There are indications that oxygen stress changed at the turn of the century and worsened since the 1950s coincident with indicators of increasing biological productivity.[39] The fact that the most dramatic changes in the continental shelf ecosystem have been since the 1950s, coincident with an increase in nitrogen load, points to aspects of human ecology, and not to changes in the delivery of the water at the terminus of the system (i.e., effects of leveeing or lack of overland flow), as the proximal causal factor.

V. FACTORS NOT INFLUENCING HYPOXIA

Identification of potential human activities or natural events and cycles that might affect the development of hypoxia or its historic increase is important because management strategies need to address factors that are relevant, important and controllable. Consideration of alternative causes is important, because once dismissed, management options that focus on them become moot. Based on the above discussion, it is clear that worsening hypoxia on the Louisiana continental shelf is *not* caused or influenced by:

- the oxygen minimum layer of deeper offshore waters
- changes in the quantity of freshwater discharge
- leveeing of the lower Mississippi River or lessening of overbank flooding since the turn of the century

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32. *See id.*
33. *See* Turner & Rabalais, *Mississippi River Water Quality*, *supra* note 20, at 143.
34. Silicate is important to the growth of diatoms, the base of the food web.
35. *See* Rabalais et al., *Nutrient Changes in the Mississippi River*, *supra* note 1, at 391.
36. *See* Turner & Rabalais, *Coastal Eutrophication*, *supra* note 26, at 620.
37. *See* Turner & Rabalais, *Mississippi River Water Quality*, *supra* note 20, at 144.
38. *See* Turner & Rabalais, *Coastal Eutrophication*, *supra* note 26, at 620.
39. *See* Turner & Rabalais, *Mississippi River Water Quality*, *supra* note 20, at 144.

- carbon and/or nitrogen from wetland loss on the periphery of the continental shelf
- export of nutrients from local nutrients
- riverine carbon or toxic chemical loading
- long-term climate changes

VI. ANTHROPOGENIC INFLUENCES

Evidence associates oxygen depletion with changes in landscape use and nutrient management that result in nutrient enrichment of receiving waters.[40] Nutrient flux in coastal systems, while essential to the overall productivity of those systems, has increased over time due to anthropogenic activities and has led to broad-scale degradation of the marine environment.[41]

The most noticeable change in human activity in the watershed since the 1950s is in fertilizer application rates and changes in land use that affect the fate and transformation of nutrients before they reach the Gulf of Mexico.[42] Animal husbandry practices have shifted to higher intensity operations.[43] A small percentage of atmospheric nitrogen reaches the watershed, but it has likely increased over time.[44] Wastewater treatment effluent is a small percentage of the nitrogen load.[45] Efforts to manage nutrients should focus on those aspects of landscape architecture and human activities that show a documented effect in increasing eutrophication and worsening oxygen stress and on those that can be controlled.

VII. CONCLUSION

The northern Gulf of Mexico adjacent to the discharge of the Mississippi River system is an example of a coastal ocean that has undergone eutrophication (increased rate of primary production) as a result of increasing nutrients and that has worsened hypoxic conditions on decadal time scales. Whole system management of the entire watershed where most of the changes have occurred over the

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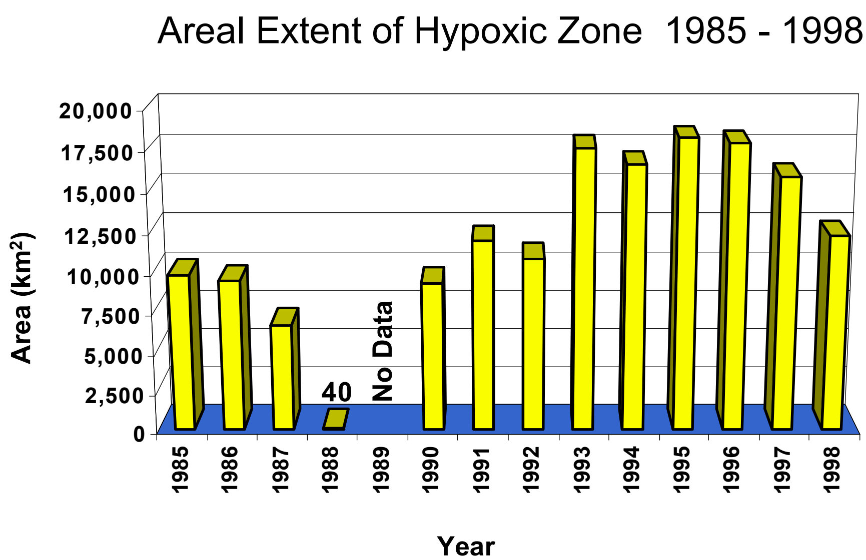
40. *See* Rabalais et al., *Nutrient Changes in the Mississippi River*, *supra* note 1, at 387.
41. *See* Turner & Rabalais, *Coastal Eutrophication*, *supra* note 26, at 620-21.
42. *See* Turner & Rabalais, *Mississippi River Water Quality*, *supra* note 20, at 140.
43. *See* D.A. GODSBY ET AL., REPORT TO WHITE HOUSE OFFICE OF SCIENCE AND TECHNOLOGY POLICY, COMMITTEE ON ENVIRONMENT AND NATURAL RESOURCES, HYPOXIA WORK GROUP, MISSISSIPPI RIVER/GULF OF MEXICO WATERSHED NUTRIENT TASK FORCE, TOPIC #2, FLUX AND SOURCES OF NUTRIENTS IN THE MISSISSIPPI-ATCHAFALAYA RIVER BASIN (1998).
44. *See id.*
45. *See id.*

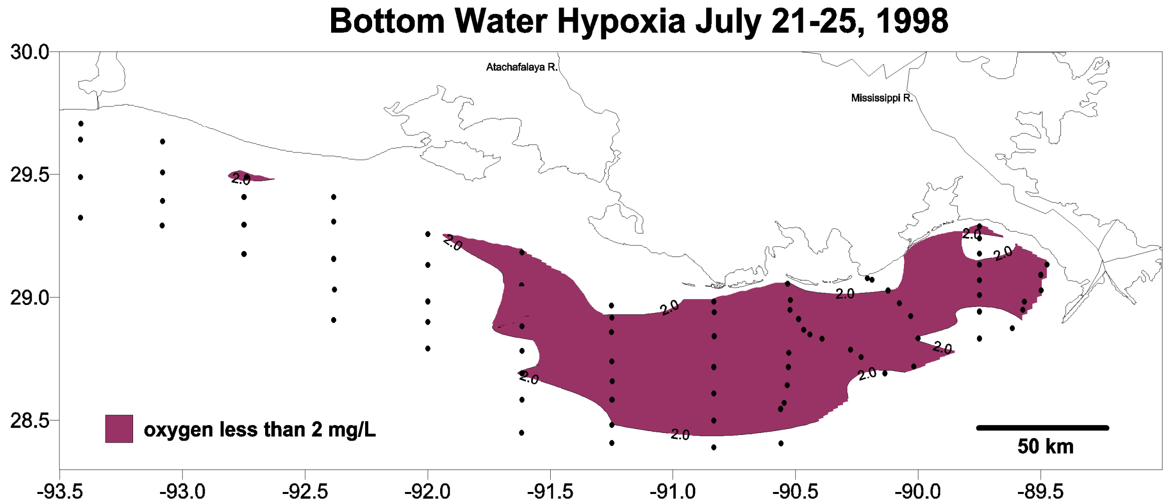
last several decades is a necessary step in alleviating the problems at the terminus of the River in the Gulf of Mexico.

APPENDIX 1[46]



46. *See* Rabalais, *1993 Mississippi River Flood*, *supra* note 2, at 175 (updated to reflect data through 1998).

APPENDIX 2[47]



47. *See* Nancy N. Rabalais et al., Unpublished Data (1999) (data on file with author).