December 16, 1999

Gulf of Mexico Hypoxia Working Group
National Oceanic and AtmosphericAdministration
National Centers for Coastal Ocean Science, Room 9127
1305 East West Highway
Silver Spring, MD 20910

To whom it may concern,

Please accept the attached document as a contribution to the Gulf of Mexico Hypoxia Integrated Assessment.

This white paper addresses issues raised by the report of the University of Alabama entitled *The Role of the Mississippi River in the Gulf of Mexico Hypoxia*, which was referenced in various public comments on the technical reports on which the assessment is based.

An earlier draft of my paper was distributed prior to and discussed at the December 3 workshop held in St. Louis. The current version reflects changes and additions resulting from those discussions.

I am submitting this evaluation as an individual scientist knowledgeable about scientific issues related to eutrophication, including hypoxia in the Gulf of Mexico.

Sincerely yours,

Donald F. Boesch
Professor

Attachment

The Role of the Mississippi River in Gulf of Mexico Hypoxia
Oversimplifications and Confusion

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November 29, 1999

A report produced for The Fertilizer Institute by the University of Alabama[1] entitled *The Role of the Mississippi River in the Gulf of Mexico Hypoxia* raises several questions about whether the large-scale oxygen depletion (hypoxia) in bottom waters of the Louisiana continental shelf is the result of anthropogenic nutrient loading from the Mississippi River, as has been reported in the scientific literature and concluded by the Gulf of Mexico Hypoxia Assessment carried out under the Committee on Environment and Natural Resources[2]. The University of Alabama (UA) report calculates that "terrigenous (land-derived) organic carbon is likely to be an important component of the total organic matter flux" driving oxygen depletion in hypoxic zones. It also suggests that discharges of biologically available actually decreased since the 1950s. In addition, it draws inferences that hydrological changes in the river basin coupled with increased river flow may be responsible for increased hypoxia rather than just increased loadings of nutrients from fertilizers and other human sources.

These assertions casting doubt on the importance of increased land-derived nutrient (particularly nitrogen) loading in increasing the extent and intensity of hypoxia have been widely cited by agricultural and industrial interests, such as the American Farm Bureau Federation and The Fertilizer Institute, and some upstream states in their comments on CENR Assessment.

This white paper is not a comprehensive critique of the entire UA report, but an examination of the evidence and arguments in the report supporting its contentions that terrestrial organic loading is important relative to nitrogen, total bioavailable nitrogen loadings have actually decreased, and hydrological changes contribute to more pervasive hypoxia. It is intended to inform the CENR Assessment and address the concerns by upriver and agricultural interests—apparently bolstered by the UA report—concerning the role of anthropogenic nutrient loadings in hypoxia in the Gulf of Mexico.

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[1] Carey, A.E., J.R. Pennock, J.C. Lehrter, W.B. Lyons, W.W. Schroeder and J.-C. Bonzongo. 1999. The Role of the Mississippi River in Gulf of Mexico Hypoxia. Environmental Institute Publication Number 70. Prepared for The Fertilizer Institute by The University of Alabama, Tuscaloosa, Alabama 35487-0207.
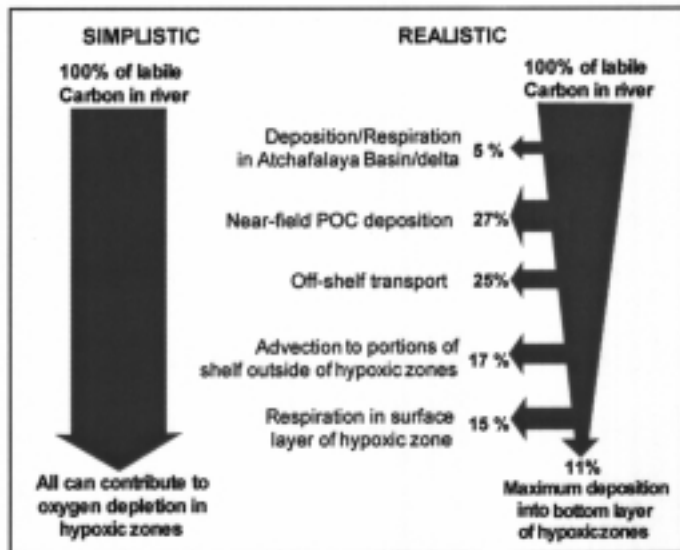
[2] Four reports produced for the CENR assessment summarize relevant literature, data and analyses: Topic 1. Characterization of Hypoxia, Topic 3. Flux and Sources of Nutrients in the Mississippi-Atchafalaya River Basin, Topic 4. Effects of Reducing Nutrient Loads to Surface Waters within the Mississippi River Basin and the Gulf of Mexico, and Topic 5. Reducing Nutrient Loads, Especially Nitrate-Nitrogen, to Surface Water, Goundwater, and the Gulf of Mexico.

Land-Based Carbon Sources are Relatively Unimportant

The UA report's premise that terrigenous organic carbon is likely to be an important component of the total organic matter flux, and thus oxygen consumption in bottom waters that become hypoxic, is based on estimates of the flux of readily degradable organic carbon discharged by the Mississippi and Atchafalaya rivers; the relationship of this flux to the metabolic demands required to deplete the oxygen in bottom hypoxic waters (quoted in the following box); and new interpretations of the ratios of stable carbon isotopes in shelf sediments that may indicate a dominant terrigenous source of organic carbon to the shelf.

> *How important could this allochthonous carbon flux be for the benthic metabolism and O_2 consumption in the nearshore and shelf region of the Gulf of Mexico? To answer this question, we have performed a rather simple-minded calculation. We have used Dortch et al.'s (1984) total benthic respiration rate from the hypoxic zone obtained in 1991 (range of 160 to 800 mg O_2 m^{-2} d^{-1}). We have taken the estimated area of the hypoxic zone for that year and multiplied the equivalent amount of carbon respired by the measured benthic respiration rate (Dortch et al., 1994) cited above, to produce an estimate of total benthic respiration in the hypoxic zone. This yields a carbon respiration or organic carbon consumption of 2.4 to $11.8x10^{10}$ moles of carbon annually. This value is quite similar both to that of Trefrey et al. (1994) and the mean USGS flux discussed above, even if we assume that only 35% (Ettekott, 1988) of the total organic carbon is labile or oxidizable ($17x10^{10}$ moles C and $9.2x10^{10}$ moles C, respectively).* UA report, p. 48.

This comparison is far too simplistic in assuming that the organic carbon in the river discharges is completely conveyed, as if by pipeline, to hypoxic layers lying 30 to 380 km from the points of the river discharges. In fact, the hypoxic layers constitute only a small portion (approximately 20% or less) of the water mass on that part of the shelf influenced in one way or another by river discharges. The comparison completely neglects the losses of the allochthonous organic carbon due to advection, deposition, and metabolism en route to the hypoxic zones (schematically depicted below). Furthermore, it very probably overestimates the proportion of the organic matter that is labile and underestimates the oxygen consumption required to create and maintain bottom-water hypoxia.

Simply put, the "simple-minded calculation" in the UA report does not take into account the geography, scale and physical and biochemical processes associated with shelf hypoxia. The schematic diagram shows why only a fraction of river-borne labile organic carbon could reasonably find its way into position

to be metabolized in the bottom layers of hypoxic zones. These estimates of losses en route are in all cases conservative and, except for respiration in the surface waters above the hypoxic zone, do not include metabolic losses in transit. In reality, far less than 11% of the river's organic carbon reaches hypoxic bottom waters on the shelf. This hypothetical budget is based on the following assumptions and estimates:

Loss of C	Estimated rate	Rationale
Deposition and mineralization in Atchafalaya Basin and delta	15% of Atchafalaya flow	Huge swamp basin and emerging delta and surrounding tidal wetlands trap POC and provide opportunity for mineralization of labile organic matter.
Near-field deposition of POC	60% of the POC (POC flux is 48% of the TOC[3])	A large portion of the suspended load is deposited when river currents enter Gulf and lose momentum and as a result of flocculation. Most of the primary depositional zones around the Mississipi delta proper[4] and along the Chenier Plain coast (primary shelf depocenter for the Atchafalaya discharge) are not subject to hypoxia.
Advection of flow through Mississippi delta into deep water	50% of Mississippi delta flux	Only half of flow through the Mississippi delta proper stays on shelf and flows to the west; much small proportion of this flow may remain on shelf under very high discharge and west wind conditions.
Transport to portions of the shelf outside the hypoxic zone	40% of remaining labile TOC	The area on the shelf over which the river effluents spread (as indicated by reduced surface salinity) is far larger than the hypoxic zone, extending both farther inshore and offshore.
Respiratory consumption in surface waters over hypoxic waters	80% of the remaining labile DOC	Hypoxic bottom waters originate from the deeper shelf and mix little with surface waters. Although terrigenous POC may sediment directly into this layer from river-influenced surface waters, DOC must be assimilated by microorganisms in the surface mixed layer, which consume most of this carbon through their respiration. The assumption that 20% is biodeposited to the bottom layer is very liberal given the known efficiency of retention within the microbial loop.

The assumption that 35% of the TOC flux of the Mississippi-Atchafalaya rivers is readily oxidizable or labile is very probably too high. Although this value was taken from a paper on organic fluxes in world rivers, the Mississippi is a long, nutrient-rich and well-oxygenated river that provides ample opportunity for mineralization of organic matter during transit. It is not clear how a significant portion of the labile carbon pool would travel down the river undegraded over weeks to months only to be rapidly degraded in
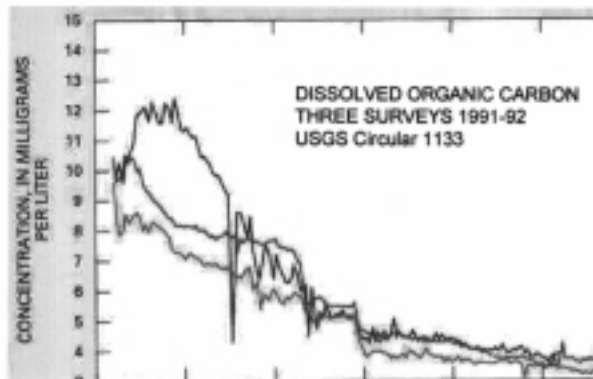
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[3] Although the UA report cites Trefrey et al. that 66% of the TOC is POC and 34% is DOC, more recent and extensive sampling by the USGS NASQAN for the lower Mississippi and Atachafalaya (1996-98) indicates that the ratio of TOC:DOC in terms of average concentration is 37:63, but the ration in terms of average annual flux is 48:52. This assumes POC and DOC are equally labile.

[4] As depicted in the UA report (Fig. 30), Trefry et al. (1994) showed that approximately half of the near bottom POC in the nearfield plume within 30 km of Southwest Pass was terrigenous in origin, reflecting the rapid deposition of suspended sediments upon leaving the turbulent flow regime of the river.

the Gulf over similar time periods during residence on the shelf, particularly in oxygen-limited sediments.

Several lines of evidence indicate that the fraction of the organic carbon loading that is labile or oxidizable is substantially less than 35%. Average concentrations of total organic carbon (dissolved and particulate) in the lower river at St. Francisville averaged 6.38 mg L^{-1} during 1996-98[5], while the mean 5-day biochemical oxygen demand (BOD) over the same period was 1.58 mg L^{-1}. It would require complete oxidation of 9% of that organic carbon pool to meet that oxygen demand if the only substance oxidized was reduced carbon (nitrite, ammonia and other oxygen demanding materials also contribute to BOD).

In addition, the longitudinal distribution of dissolved organic carbon in the Mississippi River system strongly suggests that the organic carbon contained in the lower river is a very refractory residual from the microbial degradation that takes place along the long course to the sea. DOC concentrations averaged about 10 mg L^{-1} at Minneapolis/St. Paul (nearly 3,000 km upriver from the Gulf), but declined to 4.2 mg L^{-1} at a point 1,500 km upriver from the Gulf (just below the entry of the Ohio River). DOC concentrations remained relatively constant downstream, with average concentrations dropping only to 3.7 mg L^{-1} over the remaining 1,500 km. After the confluence of the Arkansas, the last major tributary to join the Mississippi, the decline in DOC concentrations suggested that less than 7% of the DOC was degradable over the last 800 km of transit. It is reasonable to assume that the processes that degrade the DOC also act on the POC during transit down the river.

DISSOLVED ORGANIC CARBON
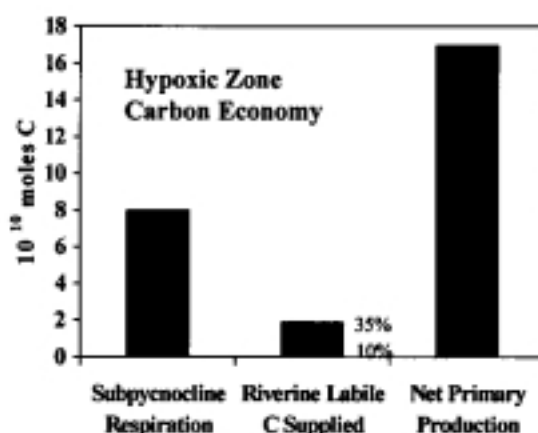THREE SURVEYS 1991-92
USGS Circular 1133

All of this indicates that the organic carbon discharged into the Gulf is predominantly refractory—the recalcitrant remains from hundreds of years of soil processing and a 3,000 km long secondary treatment system—and that the proportion of the residual that could be further degraded over time scales of weeks to months is less than 10%. Although there are other suggestions[6] that a greater percentage (up to 50%) of the particulate organic carbon discharged by large rivers such as the Mississippi cannot be accounted for in the sediments in depositional areas, this does not necessarily mean that that "missing carbon" contributes to shelf metabolism. It could be lost due to desorption and transported away as dissolved organic carbon or other mechanisms.

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[5] USGS NASQAN data.

[6] Keil, R.G. et al. 1997. Loss of organic matter from riverine particle in deltas. Geochemica Cosmochemica Acta 61: 1507-1511.

Moreover, the use of benthic respiration as a basis of comparison with terrigenous organic inputs ignores the role of respiration in the bottom layers of the water column in depleting oxygen. Water-column respiration in the isolated bottom waters is at least equal to benthic respiration and may be 2 to 3 times the rate of benthic respiration[7]. The UA report did not consider other published reports[8] of total respiration below the pycnocline in hypoxic areas, which estimate the annually integrated subpycnocline respiration to be 197 g O_2 m^{-2} yr^{-1}. Using the same C:O and areal assumptions as the UA report, this translates to an annual requirement of 8.0×10^{10} moles of C to satisfy the observed metabolism. This is within the range, but above the mean, of the two bounding estimates of the UA report.

Given that not more than about 11% of the terrigenous labile organic matter could contribute to hypoxia and less than 35% of this organic matter may actually be oxidizable within the time frames in which hypoxia develops, the contribution of terrigenous organic sources to hypoxia has to be a very small part of the carbon respired in hypoxic waters. The UA report states that: " even if only 10% of the total organic carbon flux could be metabolized within the bottom waters or at the sediment-water interface, this could account for a significant portion of O_2 loss." Because of the losses en route, it is likely, based on the calculations developed here, that not more than 4% of the total terrestrial organic flux is metabolized within hypoxic layers and this proportion may be less than 1% if only 10% of the organic carbon is labile. Furthermore, in either case, this would account for only a small part of the subpycnocline respiration.


On the other hand, the production of plankton carbon in the surface waters overlying hypoxic waters (summarized in CENR report 1) is 9 to 32 times greater than the maximum amount of riverine labile carbon reaching hypoxic zones, depending on assumptions about the lability of the terrestrial carbon. If, as argued above, the proportion of the degradable organic carbon is closer to 10%, this would suggest that terrestrial organic carbon sources could be responsible no more than about 7% of the oxygen respiration below the pycnocline, with the remaining carbon coming from the surface production (44% of which would be required to support subpycnocline respiration) or the productive coastal boundary layer along the inshore border of the

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[7] CENR Report 1 and Bierman, et al. (1994). A preliminary mass balance model of primary productivity and dissolved oxygen in the Mississippi River plume/inner Gulf shelf region. Estuaries 17: 886-899.

[8] Justic, 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. Limnology and Oceanography 41:992-1003.

hypoxic zone. Of course, this pertains to the average conditions for the hypoxic zone; nearer the rivers a greater percentage could be accounted for by terrigenous carbon, while regions remote from the rivers receive insubstantial labile terrigenous carbon. Curiously, the UA report pays no attention to the losses of terrigenous organic carbon to sedimentation, dispersion and metabolism as it is transported over distances of 30-380 km during the several weeks[9], yet devotes an appendix to calculations that seek to demonstrate that less than 25% of the marine organic carbon produced in waters overlying hypoxic zones is deposited to the bottom—over a vertical distance of 10 m or less. Actual published observations from sediment traps show that there is sufficient seston deposition from surface production, especially during the spring, to supply the organic carbon required (Topic 1 report).

The UA report also suggests that large injections of terrigenous organic carbon during floods may have consequences for oxygen depletion in subsequent years. Considered in the context of the previous discussion, this would have to assume that the small labile portion of this organic matter that is deposited on the shelf would remain largely undegraded over six months in relatively warm Gulf of Mexico bottom waters until stratification sets up the next year and then be actively mineralized. Also, while the multi-year consequences of flood events deserve more attention, it is important to keep in mind that these floods also inject elevated masses of nutrients, which by stimulating plant production greatly magnify the pool of labile organics on the shelf (see below). Organic matter produced *in situ* as a result of such pulses could also remain stored in the shelf system until hypoxia sets up in the following spring. At least in the 1993 flood, a much larger than normal portion of the flow through the Mississippi delta proper was lost from

the shelf environment as a result of the strong discharge jet that propelled the plume onto the slope and wind forcing of currents toward the east. So, a smaller than normal proportion of the organic carbon spike could be "credited" to the carbon metabolism of the Louisiana shelf. Again, this underscores the need to consider the importance of interannual inputs of both carbon and nitrogen from a dynamic and geographically realistic perspective rather than as a simplistic black box.
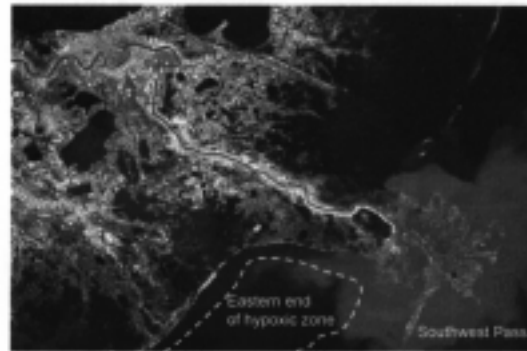
Concomitant with the greatly diminished suspended particulate concentrations experienced in the lower Mississippi River during the last half of the 20th century (50 to 70 % reductions[10]), the concentrations and loadings of organic carbon have also declined.

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[9] Mean currents available to transport DOC or POC are quite slow, <25 cm sec-1 in the coastal boundary jets and slower in most of the region experiencing hypoxia (Wiseman, W.J. and F. J. Kelly. Seasonal variability within the Louisiana Coastal Current during the 1982 flood season. Estuaries 17:732-739.)

[10] Kesel, R.H. 1988. The decline in the suspended load of the Lower Mississippi River and its influence on adjacent wetlands. Environmental Geology and Water Sciences 11:271-281.

Thus, if it were primarily injections of terrigenous organic carbon that were fueling hypoxia on the shelf, the intensity of hypoxia should have decreased since mid-century. Biological and chemical indicators in Mississippi Delta Bight sediments, as summarized in the CENR Topic 1 report, suggest the opposite is true.

Stoichiometry and Cycling of Carbon and Nitrogen

If one were to make the case that terrigenous organic carbon is an important contributor to the metabolism depleting oxygen on the shelf it would seem that a requisite part of that argument should be comparison with other sources of organic carbon, particularly plankton production. However, the UA report makes no attempt to compare directly the contributions to shelf hypoxia of terrigenous carbon versus *in situ* marine production stimulated by terrigenous nutrient inputs. How then could one conclude which is more important? A first-order approach to determination of relative importance is the comparison of the flux of labile organic carbon from the rivers to the primary production that could be supported by the flux of bioavailable nitrogen or phosphorus.

First, let us summarize the various estimates of contemporary carbon and nitrogen flux from the Mississippi-Atchafalaya River system:

Component	Average annual flux (10^{12} g)	Source
Total organic carbon, 1973-95	2	Carey et al. (1999)
Total organic carbon	5.76	Trefrey et al. (1994)
Total organic carbon, 1996-98	5.80	USGS NASQAN data
Total nitrogen, 1980-96	1.57	Goolsby et al. (1999)
Total nitrogen, 1996-98	1.33	USGS NASQAN data
Inorganic nitrogen 1980-96	0.99	Goolsby et al. (1999)
Inorganic nitrogen 1996-98	0.99	USGS NASQAN data

Even using the higher values for total organic carbon flux, a few straightforward calculations quickly lead one to the conclusion that terrigenous nitrogen has to be far more important than terrigenous organic carbon without having to address the losses of carbon due to advection, deposition and metabolism considered above.

Average annual flux	10^{11} moles	Marine C/ Riverine C
Riverine inorganic nitrogen	0.71	
Riverine total organic carbon	4.83	
Riverine labile organic carbon (@35% of total)	1.69	
Riverine labile organic carbon (@ 10% of total)	0.48	
Marine organic carbon directly supported by new riverine nitrogen (Redfield atomic ratio of 106/16 = 6.625)	4.68	2.8-10.2
Marine organic carbon supported by new and recycled nitrogen (average recycling = 4)	18.74	11.1-39.0

This actually underestimates the relative mass of utilizable N because it excludes all organic N, even though some of the organic N is either directly utilizable by phytoplankton or would be released as useable ammonium following heterotrophic mineralization. Even if fully 35% of the riverine organic carbon were labile, just the readily bioavailable, inorganic nitrogen discharged by the rivers would support the production of almost three times as much readily labile organic carbon by the marine plankton. However, the real impact of the nutrient additions is that they are recycled, used again and again to produce more marine carbon. As discussed in the UA report (p. 41) the phytoplankton production beyond the immediate dilution plume close to the river passes is based on ammonium and other recycled compounds. Evidence reviewed in CENR Report 1 suggests that an atom of nitrogen discharged by the river is used to produce organic carbon an average of four times before it is lost due to burial, denitrification of flushing off of the shelf. This is plausible, even conservative, based on known recycling rates in other coastal ecosystems[11]. This means that at least 11 times more labile organic carbon is produced by phytoplankton supported by terrigenous nutrients than directly provided in the form of terrigenous carbon, and this might be 39 times as much if only 10% of the riverine organic carbon is effectively labile.

This difference of an order of magnitude or more is consistent with the previous estimation that terrigenous organic carbon could contribute less than 10% of the oxygen-consuming carbon in hypoxic waters. It further suggests that if nitrogen is subject to the proportionally similar advective, depositional and metabolic (in this case denitrification) losses as river-supplied organic carbon, the nitrogen inputs are sufficient to match the respiratory demands resulting in hypoxia.

The magnifying effects of the stoichiometry and recycling of nutrient additions in comparison to organic carbon inputs to coastal ecosystems have been widely appreciated over the thirty years since the landmark paper of Ryther and Dunstan[12]. As a result, the science and management of coastal water quality shifted from a preoccupation with biochemical oxygen demand (BOD) of organic wastes to an emphasis on nutrient loadings and dynamics. Organic loadings from point sources produced intense, but relatively localized impacts, mainly on the benthic environment as influenced by deposition of highly labile particulate organic carbon. These impacts have been largely ameliorated as a result of waste treatment (solids removal and secondary treatment). On the other hand, the more widely distributed and often distant consequences of anthropogenic nutrient inputs, including those from the harder-to-control nonpoint sources, have been documented, analyzed and modeled in many areas around the world. Nutrient enrichment has been accepted as a major cause of environmental degradation in many regions of the US, Europe and Japan, where major commitments to reduce nutrient loadings have been made by governmental, industrial and agricultural sectors. The UA assessment does not consider this 30-year development in science and environmental

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[11] Howarth, R.W. 1991. Comparative responses of aquatic ecosystems to toxic chemical stress, p. 169-195. In J. Cole, et al. (eds.). Comparative Analysis of Ecosystems. Springer-Verlag, N.Y.

[12] Ryther, J.H., and W.M. Dunstan. 1969. Nitrogen, phosphorus and eutrophication in the coastal marine environment. Science 171:375-380.

management regarding the importance of nutrients in coastal eutrophication, not to mention the even longer experience with managing nutrient enrichment in lakes.

Raising of the organic carbon argument by consultants for the fertilizer industry is reminiscent of arguments of the detergent industry that it was organic carbon and not phosphorus that was causing lake eutrophication. Once we moved past that red herring, thanks to classic studies in the Canadian lakes and the Great Lakes, society was able to adapt to low phosphorus detergents and routinely apply phosphorus removal in waste treatment. Our laundry remains clean, but many lakes are much cleaner as a result!

Meanwhile, the total nitrogen flux of the Mississippi River system has more than doubled since the publication of the Ryther and Dunstan classic (comparison of 1969, a year of about average flow, with the 1986-95 mean, Topic 3 report), while the terrigenous organic carbon loading has declined (UA report)!

Sediment Leftovers

Carbon isotopic studies of Gulf of Mexico continental shelf sediments, up until 1997, had concluded that 50% or more of surficial organic matter derived from marine or phytodetrital sources. However this came into doubt when Goñi et al. (1997) pointed out that the ^{14}C "ages" of surface (0-2 cm) sediments are very old (~2600 to 6800 years).

Using Gulf of Mexico shelf and slope sediment cores collected in 1987, Goñi et al. (1998) have recently shown the importance of land-derived C_4 plant (corn and grasses) organic matter in these sediments. They also conclude that this material is old, highly degraded and has been cycled through the soil several times. UA report p. 47

Based on these recent published reports, the UA report questions the interpretation of several studies of the ratio of stable isotopes of carbon (^{12}C and ^{13}C) that concluded that away from the vicinity of the river mouths, the organic carbon in Louisiana shelf sediments is predominantly phytoplankton-derived. However, none of the sediment samples reported on by Goñi and colleagues[13] was collected from the inner-mid shelf hypoxic zones, rather their samples were from the continental slope at water depths of 74 or more, particularly down the prodelta slope, where most of the river-derived POC is deposited. Furthermore, Goñi et al. suggest that little of the C4 terrestrial plant carbon that confuses the interpretation of the ^{13}C deposits on the shelf as opposed to the slope. Nonetheless, these new interpretations of the ^{13}C do raise some important questions that merit further study and caution care in interpretation of these ratios. Nonetheless, the changing ratios found with distance from riverine sources, the differences in isotope ratios in contemporary river-borne organic carbon and shelf sediments, and the changes in isotope ratios in sediments laid down during the late 20th century reported by previous investigators and summarized in Report 1—all of which are consistent with a marine origin of the carbon—still require explanation.

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[13] Goñi, M.A. et al. 1998. A reassessment of the sources and importance of land-derived organic matter in surface sediments from the Gulf of Mexico. Geochemica et Cosmochemica Acta 62:3055-3075.

Furthermore, if most of the organic carbon in shelf sediments is thousands of years old (from the time it was originally incorporated in plant tissue), then the carbon isotope ratios tell us nothing regarding the contemporary sources of the new, labile organic carbon that is responsible for shelf hypoxia. If the carbon were indeed thousands of years old, it would suggest that the majority of the organic carbon pool in the sediments is very refractory material. Phytoplankton-derived carbon could be almost totally labile, fuel respiration, and contribute little to the sediment carbon trash heap. To deduce the relative importance of contemporary supplies of organic carbon from analysis of remnants thousands of years old might then be analogous to describing the diet of modern Americans solely from studies of Indian shell middens.

Total Available Nitrogen Loadings Have Decreased

Recent work by Mayer et al. (1998) has indicated that although the dissolved inorganic nitrogen (DIN) concentrations of the Mississippi River have increased over time from 1950-52 until 1973-82, the amount of "labile" or bioavailable particulate nitrogen (LPN) has decreased.

If one argues, as Mayer and colleagues have, that this LPN can be rapidly solubilized and utilized by coastal phytoplankton, the actual bioavailable N introduced to the shelf from the Mississippi River may have actually decreased from 1950-52 ti 1973-82 (Figure 31). UA Report, p. 48.

Do the results of Mayer et al. (1998) truly demonstrate that total labile nitrogen loading has actually decreased since 1950s as a result of declines in PN as suggested in the UA Report?

Mayer et al. made only two measurements of total nitrogen in suspended particulates in the Mississippi River in 1994 and 1997, yielding estimates of 2.5 to 3.5 mg g^{-1}. All estimates of PN concentrations for various time periods were made by multiplying these concentrations by Meade and Parker's (1985) estimates of average suspended particulate material concentrations. There are several problems with this approach:

1. All extrapolations were based only on these two estimates. Using the average of 3 mg g^{-1} and Meade and Parker's average SPM for 1973-1982, the volumetric PN concentration would be 1.7 mg L^{-1}, which is 4.5 times higher than the average PON concentrations (1080-98) measured by the USGS NASQAN based on a large number of samples over many months and years.

2. No actual measurements were made for any of the time periods considered (50-52, 53-72, and 73-82). The estimates for these periods assume the same concentrations of PN per mass of suspended particulates, despite the fact that the factors acting to reduce SPM concentrations by half could have also affected these concentrations. Moreover, the factors causing the observed increase in DIN during these time periods and between 1982 and the time of collection of Mayer et al.'s samples could have also affected the PN.

3. The assumption regarding how much of the PN delivered by the river is bioavailable in the Gulf is based on differences in the concentrations of PN per mass of SPM

(based on just two samples) to the concentrations, adjusted for particle surface area effects, in 15 surface sediment samples in the depocenter offshore. Not only is this highly dependent on scant but much higher estimates of particulate nitrogen concentrations that the voluminous USGS data, but also on numerous assumptions about the contemporary age of the surface sediments and unknown gains and losses of N in the sediments (e.g. denitrification) as discussed by Mayer et al. If the concentrations of the PN in these two SPM samples are indeed too high an estimate of average concentrations by a factor of 2, much less more than 4, there would be no evidence that any of the riverine PN is labile, as is the case for several other rivers Mayer et al. studied.

Using the more data-rich USGS estimates (1980-98) of PN (27 μM reported as PON) and DIN flux (108 μM) in recent years, assuming that the PN/SPM ratio is constant and the same SPM concentrations, DIN + PN concentrations would have increased by 12% since 50-52, despite a 47% decline in PN. Because only a fraction (<<50%) of the PN and DON is bioavailable, the increase in labile N must be substantially greater than that.

Long-Term Hydrologic Changes

> *[T]here is evidence of a significant increase in the discharge of the Mississippi since 1967. This amounts to approximately an 11% increase in river discharge and is most likely the result of climate and precipitation changes and also in reservoir operation by the Corps of Engineers since that time. Discharge to Atchafalaya Bay has also increased during this century as a result of artificial control of flow.* UA report p. 32
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> *[A]s a result of the channelization and leveeing of the river, floodwaters spend significantly less time in the historical floodplain during flooding events. This results in more rapid transit of river water to the Gulf and less opportunity for interaction with wetlands in the floodplain where nitrate removal would occur. Both of these factors reduce the opportunity for nitrate removal via denitrification.* p. 34

Climate and, consequently, river discharge vary dramatically. We have known that for a long time. Furthermore, we are becoming increasingly aware that there may be long-term, secular trends superimposed on this variation. It is also clear that humankind's plumbing of this great river system has affected how much freshwater flow and its constituents are delivered to the Gulf, and when and where. But, the appropriate question is: Could these climatic variations and changes and hydrological modifications alone, without any increases in anthropogenic loadings of nutrients in the watershed, have caused observed changes in the delivery of nutrients and hypoxia in Gulf?

Much attention is paid in the UA report about whether the hypoxic zones have increased since systemic mapping began in 1985 and following the 1993 flood and the relationship of these trends to river flow and nutrient delivery. I do not believe that one can conclude that nutrient loading or hypoxia have increased during the 1980s and 1990s. The interannual variations in estimates of the extent of hypoxic bottom waters are functions of interannual variations and seasonal timing of the delivery of fresh water and nutrients, meterological and oceanographic forces that affect stratification (e.g. formation of a secondary thermocline causing an oxycline), mixing and currents, and the imprecision of the survey as a means to characterize the extent of hypoxia for the year (a still frame in an

action-packed movie). The big changes in the trophic regime on the inner shelf that led to more frequent, persistent, severe and extensive hypoxia by all evidence (from the sediments and river flux) and reasoning occurred earlier, particularly during the 1950s, 1960s and 1970s.

Much is also made in the UA report of a "jump" in river flow after 1967, but careful examination of the graphs of annual mean flow reveals that flows during the period 1967 to 1972 were at or actually below the 1817-1966 mean. The major features of the flow record after 1972 are the two highest flow years on record, 1973 and 1993, coming twenty years apart. Without those two years the 1967-1995 mean flow is very close to the 1817-1966 mean. Should one conclude that there has a secular jump in river flow just because of the coincidence of two 100+ year floods within a twenty year period? Nonetheless, the Topic 3 report also concludes that there has been an increase in flow, so long-term changes in river flow must be considered, both retrospectively and prospectively.

How then has increased flow affected nitrogen flux during a period in which we know the loadings of soluble and highly reactive nitrogen in the watershed have also increased? Fertilizer consumption also grew rapidly from the late 1950s through the 1970s (UA report Fig. 13). Atmospheric deposition of nitrate in the watershed also grew during this same period as it did throughout eastern North America. Nitrate concentrations in the river were rising during the 1960s (UA report Fig. 12), but fluxes did not grow greatly until the 1970s when river flow increased dramatically with the record breaking 1973 flood. Flow during 1973 topped the legendary 1927 flood year and brought down more fresh water, and probably more organic carbon, to the Gulf than the better studied 1993 flood. But something seems to have happened with regard to nutrient delivery of the river between 1973 and 1993.

Comparison of nitrogen flux to river flow for the eight highest flow years between 1973 and 1993 reveals some interesting patterns (see following graph). First, organic nitrogen flux seems not to be influenced by flow, at least at these high flow rates. There is no obvious temporal trend. High river flows after 1975 have delivered far more nitrate than previously. Coincidentally, this was a time near the end of the rapid growth in the consumption of nitrogen fertilizers (UA report Figure 13). To determine if there is a linkage would obviously require better understanding of the saturation, time lags, and small scale hydrology, but the point here is that the changes in nitrate delivery were not due to changes in hydrology alone.

The UA report correctly observes that exclusion of flood plains, channelization of flow within levees that prevents dispersion of flow through the wetland-estuarine deltaic plain, and increased flow down Atchafalaya all could work to increase the amount of nutients the river system delivers to the Louisiana shelf. However, all of these changes occurred before the rapid increase in nitrogen flux and the apparent increase in hypoxia evident in the sediment record, both post-1950s (see Appendix). The levees cutting off flood plains were essentially completed well before then, the Lafourche distributary had been closed (1904) and the Atchafalaya had already captured approximately 30% of combined river

flow by 1950 (Topic 1 report, Fig. 32). No substantial over-bank flow across the deltaic plain has occurred since the 1927 flood. While reconstructing wetlands in the watershed, reopening flood plains, management of Atchafalaya flow, and diversion of lower river flows through deltaic wetlands may all be important in reducing nutrient delivery to the Gulf in the future, none of these geomophic/hyrologic changes appears to be primarily responsible for the late 20th century intensification of hypoxia.
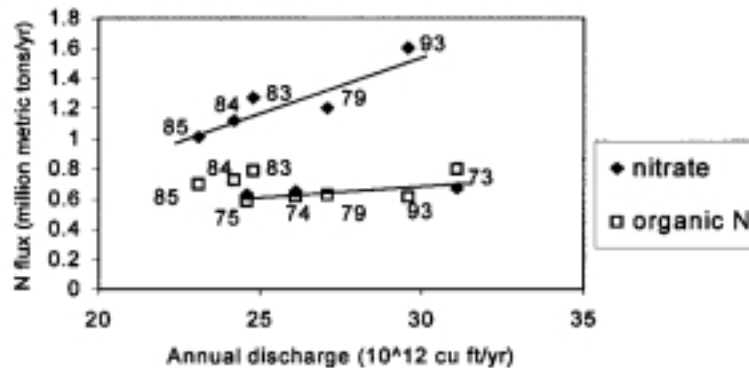
Discharge from UA report; N flux from CENR Topic 3 report

False Paradigm Conflicts

> *Currently, the data are consistent with the eutrophication paradigm but are insufficient to allow us to distinguish between the quantitative roles of inorganic nutrients and organic carbon on the fertilization processes compared to the effects of stratification on the fertilization processes versus the effects of stratification on the eutrophication process.* UA report p. 55

The UA report outlines three "paradigms" for oxygen depletion in Gulf of Mexico bottom waters (p. 8-9, Figure 3): (1) **eutrophication**, involving the increased deposition of organic matter produced *in situ* by phytoplankton stimulated by an increase in nutrients, especially nitrogen; (2) **terrestrial organic matter loading** in which the microbial degradation of organic matter transported in rivers induces oxygen depletion; and (3) **stratification**, wherein strong density differences between fresh surface and salty bottom waters inhibits mixing and prevents the exchange of oxygen to bottom waters.

The UA report introduces unnecessary confusion in understanding and polarity in perspectives in its confection of three "paradigms." There is but one paradigm here, the eutrophication paradigm. It encompasses multiple sources of organic matter and the influences of density stratification of water masses.

Eutrophication has been defined as the increase in organic loading to an aquatic system, be it from allochthonous organic matter or autochthonous biological production

stimulated by nutrient additions[14]. Clearly, the metabolism of all coastal ecosystems is based on allochthonous and autochthonous organic carbon; it is a question of proportion, not of one state or another. Based on the rationale developed above, allochthonous organic carbon, while contributing to the pool of organic carbon, can support but a minor portion of the metabolism over the more than 10,000 km^2 of continental shelf influenced by seasonal hypoxia. Besides, by all accounts, human activities have resulted in declining terrigenous organic loadings and diminished lability of this organic matter during the last half of the 20th century, a period during which nitrate flux tripled (Topic 3) and the sediment record reveals organic deposition and hypoxia increased. Taken on its own, the evidence from the northern Gulf of Mexico strongly supports increased nutrient loadings rather than terrigenous organic carbon inputs as the reason for this eutrophication. Considered in the context of the global scientific understanding of eutrophication causes and trends, uncertainties diminish even more.

Similarly, the eutrophication paradigm (a paradigm in the sense originally used by Thomas Kuhn[15] is not simply a hypothesis but a set of causal explanations widely accepted within and used in practice by the scientific community) includes the notion that density stratification is necessary for the development of hypoxia in bottom waters[16]. Nutrients and stratification are not competing hypotheses, but interacting factors. In fact, variations in river flow affect both the delivery of nutrients but also the buoyancy of surface waters, and thus the strength of stratification. If the Louisiana shelf waters were not stratified, there would be no hypoxia. Seasonal destratification and mixing from storms demonstrate that every year. The driving force of river flow means that nutrient delivery and stratification strongly covary. By the same token, if there were no readily oxidizable organic carbon in the ecosystem, by what process would the oxygen in the isolated bottom layers be depleted?

The causes of stratification and its role in inducing hypoxia are described in the Topic 1 report, which makes it clear that stratification is a requisite condition. Rather than arguing whether changes in the delivery of fresh water are responsible for increased hypoxia as opposed to increased nutrient loading when both factors may have, in fact, changed, it would be more appropriate and useful to pose the following question: Given the changes in and variability of flow, what would be the extent and severity of hypoxia had nutrient concentrations of the effluents not increased? This question is partially approached by the modeling in the CENR Topic 4 report. The model estimated that, for three years modeled, if nutrient loading were 20 to 30% less (river flows and water mass structure held constant), bottom water dissolved oxygen would have been 15 to 50% higher. These at-least-internally-consistent predictions together with the historical reconstructions support the conclusion that reductions in nutrient loadings would reduce

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[14] Nixon, S.W. 1995. Coastal marine eutrophication: a definition, social causes, and future concerns. Ophelia 41:199-219.

[15] Kuhn, T.S. 1962. The Structure of Scientific Revolutions. University of Chicago Press, Chicago. 212 p.

[16] Hypoxia occurs in unstratified coastal waters only in poorly flushed backwaters where intense organic loading or over-night respiration is sufficient to deplete the oxygen inventories faster than they can be resupplied by diffusion or photosynthesis.

the extent and severity of hypoxia in the future. This conclusion is bolstered by comparative observations of the dramatic contraction of the area of hypoxia on the northwestern shelf of the Black Sea during the 1990s that coincided the substantial reductions in nitrogen concentrations in the Danube River, which in turn followed the large reductions in fertilizer use as a result of *perestroika* in eastern Europe[17]

The question of how much hypoxia would be alleviated in the future if nutrient fluxes from the rivers were reduced is a legitimate one. This should be the subject of future research and modeling to inform the policy process, but the answer will remain somewhat uncertain because of the influence of meteorologic and oceanographic variability. However, it is abundantly clear that, short of building a conduit for direct discharge into the deep Gulf, reduction of upstream sources of nutrients or restoration of aquatic environments that trap them en route is the only thing that society can do to reduce the scale and intensity of hypoxia on the Louisiana-Texas shelf.

Historical Perspective

It is important to consider all the claims regarding causes of hypoxia on the inner Louisiana-Texas shelf in historical perspective (see Appendix for chronology). Some factors may be important on a transient (real time or interannual) basis, but are not the cause of secular (long-term) changes in the spatial and temporal extent or severity of hypoxia. The following is an attempt to provide such a perspective, the intent of which is to organize and clarify the confusion created in the UA report. It considers the four explanations offered as competing in the UA report (the three "paradigms" plus the factor of increased freshwater discharges, which is related to the issue of stratification).

As demonstrated above, riverine organic carbon sources cannot be a major factor today and could not be related to the increased organic enrichment during the second half of the 20th century (as evidenced in the sediment record) because particulate organic carbon loadings have decreased. Nutrient loading (particularly bioavailable nitrogen), on the other hand, is the driver of the organic carbon budget of the hypoxic zones of the shelf. The fact that nitrate loadings have increased dramatically during the last half of the century—and were very likely elevated above pristine conditions before then—coupled with evidence and strong arguments for increased organic production on the shelf support the conclusion that nutrient-eutrophication is the primary cause of secular changes in hypoxia.

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[17] Mee, L.D. and G. Topping (eds.). 1999. Black Sea Pollution Assessment. Black Sea Environmental Series Vol. 10. UN Publications, New York.

Factor	Short-term (days-a few years)	Long-term (decades)
Riverine organic carbon	Relatively unimportant over the hypoxic zone, may be more important near the river sources	Unimportant, loadings have decreased substantially during the 20th century
Riverine nutrients	Important factor: stimulates the production of the vast majority of the organic matter that, on decomposition, depletes the dissolved oxygen	Dominant factor affecting long-term changes in hypoxia: flux of nitrate increased 3-fold between 1970 and 1983, but increased flux of utilizable N probably began during late 19th century with land-clearing and cultivation.
Water column structure and circulation	Important factor: extent of hypoxia depends on current patterns, wind mixing, and intrusions of salty bottom water (secondary pycnocline).	Increased flows down the Atchafalaya during early 20th century influenced stratification and circulation, setting the stage for hypoxia on southwest Louisiana shelf during the latter half of the century.
Freshwater flows	Important factor affecting both nutrient flux and shelf stratification, thus playing a major role in the extent and severity of hypoxia.	Much less important than increases in nutrient fluxes. Increased 30% during 1970-83, but equivalent flows during the early part of this period transported half as much nitrate.

As explained above, stratification is a key factor that determines the extent and severity of hypoxia. Factors that influence it, including freshwater inputs, circulation, mixing and the intrusion of denser water masses from offshore, greatly influence the extent of hypoxia during a given period (month or year). For that reason, there is far too much emphasis on the relationship of the spatial extent of hypoxia during one annual survey to trends in nutrient enrichment. For the most part, those factors that affect water column structure and circulation on the shelf have not changed over time (except for changes in discharges, discussed next). The one exception is the changes in the apportionment of flow between the Atchafalaya and Mississippi deltas. However, it should be noted that at the beginning of the 20th century, the Atchafalaya was already carrying about 13% of the combined flow and this proportion reached present levels by 1950. This historical adjustment may not have "caused" hypoxia off the southwestern Louisiana shelf, but certainly set the stage for the hypoxia that has occurred as a result of nutrient enrichment of the rivers.

Finally, there is no question that the volume of freshwater discharges of the Mississippi and Atchafalaya rivers has a major effect on the extent and severity on hypoxia on the shelf. River discharges bring not only fresh water that strengthens density stratification and affects circulation on the shelf, but also nutrients that fuel the production of organic carbon. But, the timing of the discharges and meteorological and oceanographic factors also influence the extent and severity of hypoxia, causing considerable variation around any expected linear relationships between discharge and extent of hypoxia. Over the long term, however, changes in freshwater discharge have been much less important than changes in nutrient delivery in increasing hypoxia on the shelf. Recent years in which the

annual flows approximated the long-term average (e.g., 1992 and 1995) experienced extensive hypoxia.

Piecing together the evidence in a chronological timeline (Appendix) provides a mosaic that makes the sequence of multiple changes clearer. Although the Louisiana inner shelf may have experienced hypoxia, especially after floods, in the historic past, the first clear evidence of eutrophication (increasing supply of organic matter) was evidenced in the Mississippi River Bight (the eastern most part of the present hypoxic region) during the 19th century, probably as a result of large soil losses associated with land clearing. Microfossil evidence suggests that biological effects of hypoxia in this most proximal (to the river discharge) part of the region began to be witnessed in the early 20th century. It is quite possible that this hypoxia was driven by the massive terrestrial particulate organic and nutrient inputs that were experienced at this time, and consequently, limited to the Mississippi River Bight region. During the first half of this century the proportion of flow discharged through the Atchafalaya progressively increased.

Toward the middle of the century, while suspended sediments (including POC and PON) decreased as a result of post-dust bowl soil conservation and, later, dam construction, inorganic nitrogen supplies increased, first gradually, then in 60s and 70s dramatically. This infusion of biostimulatory material, the effects of which are magnified by recycling, resulted in increased intensity of hypoxia in the Mississippi River Bight and, hypothetically, significant expansion of hypoxia to the west. However, because there are few sites on the shelf outside of the Mississippi Delta Bight that experience the high sediment deposition rates needed for the types of paleo-biogeochemical studies that have been used in the Bight, no clear evidence of this post-60s expansion yet exists. The lack of highly depositional areas elsewhere in the present hypoxic region itself is a strong reason why terrestrial organic carbon deposition cannot be important in oxygen consumption processes over the broad region.

Closing

The UA report does acknowledge that terrigenous nutrient loading plays a role in shelf hypoxia. However, in its emphases on the role of terrigenous organic carbon, particulate nitrogen and river hydrology, it seeks to cast doubt on the importance of secular increases of nitrate loading and the efficacy of land-based nutrient controls. This critique has revealed that the UA report substantially misunderstands of the scale, geography and history of Gulf hypoxia; lacks balance in the treatment of biostimulatory effects of organic carbon versus nutrients; and selectively cites literature sources without careful attention to the nature of their evidence and assumptions. Furthermore, it misrepresents the extent to which physical forces, such as freshwater inputs, stratification and mixing, have already been addressed in the many scientific papers on the factors responsible for hypoxia.

In addition, other sections of the UA report betray either by lack of rigor or selective emphasis a certain bias toward the interests of sponsors. There is, for example, a very shallow and dismissive analysis of the effects of hypoxia on the ecosystem and on living

resources in which it is stated: "...Dagg (1995) recently proposed that increased primary production in Louisiana-Texas Continental Shelf coastal waters may be increasing secondary production of commercially important fishery species. Dagg suggests that any proposed decrease in riverine nutrient loading to alleviate hypoxia be weighed against the possible effects this decrease may have on species at higher trophic levels." Yet the paper cited[18] is limited to an analysis of copepod grazing rates and does not discuss increases in primary and secondary productivity, much less present evidence or reasoning to suggest that decreases in riverine nutrient loadings would affect higher trophic levels. At best, this is a serious misrepresentation.

Whether intended or not the effect of the UA report is to confuse and cloud the reader's understanding of the causes of Gulf hypoxia, rather than to clarify and illuminate. Nonetheless, it is hoped that in the long run, the report will have a positive effect by revealing uninformed viewpoints that can be corrected and legitimate issues that require further research and analysis.

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[18] Dagg, M.J. 1995. Copepod grazing and the fate of phytoplankton in the northern Gulf of Mexico. Continental Shelf Research 15: 1303-1317.

Appendix
Chronology of major events that potentially influence hypoxia on the inner continental shelf of the northern Gulf of Mexico

Period	Major Events
Pre-1900	▪ Log jam between Old River and Atchafalaya breached (1863) ▪ Extensive land clearing and cultivation in upper basin: suspended sediment load in 80s and 90s twice that of 1930s ▪ Eads begins training of delta passes (79) ▪ First organized tile drainage in Illinois (79) ▪ Increase in MR Bight primary production (biogenic silica) first evidenced in mid 1800s
1900	▪ Atchafalaya flow ca. 13% of combined flow ▪ Flow down Bayou Lafourche (15%) terminated (04) ▪ Changes in foraminiferan communities in MR Bight indicate hypoxic stress
1910	▪ Manufactured fertilizers begin to be used ▪ Land drainage increases 6 fold over two decades ▪ Floods of 1912-13 prompt Congress to authorize federal funding of levees
1920	▪ Great 1927 Flood, ultimately leads to decision to regulate Atchafalaya flow and levee and straighten river
1930	▪ Jadwin Plan levees and channel straightening essentially end overbank flow and shorten river's course by 240 km (30s-40s)
1940	▪ Growth in US consumption of manufactured fertilizers begins (ca 40) ▪ Increase of glauconite indicates greater anoxia in MR Bight (42)
1950	▪ More land is drained, area more than doubles from 50-70 ▪ Extensive dam building in Missouri and Arkansas reduces suspended sediment flux by 50% in a decade (53-62)
1960	▪ Use of nitrogen fertilizer in Mississippi Basin begins rapid growth (60) ▪ Decline in diversity of ostracods and further changes in forams in MR Bight ▪ Si:N ratios in lower river begin rapid decline from 4 to 1 (60-80)
1970	▪ Period of higher average river flows begins (72), new record flood in 73 ▪ First actual measurements of hypoxia off SE Louisiana and Texas coasts (72-74) ▪ Atchafalaya flow peaks at 35% stabilized at 30% (75-76) ▪ Doubling in deposition of marine organic carbon in MR Bight begins (ca 77) ▪ High flow in 79 transports twice as much nitrate as 73
1980	▪ N fertilizer use in basin begins fluctuating plateau ca. 7 x 1960 level (81) ▪ Systematic surveys and concerted research on hypoxia begin (85)
1990	▪ NECOP project started (90) ▪ 1993 flood results in dramatic expansion of areal extent of hypoxic waters ▪ Greatest N fertilizer use in basin (94-98) ▪ Areal extent of hypoxia greatest since surveys began in 85 ▪ Federal assessment of Gulf hypoxia undertaken (98-00)