NJDEP

Science Advisory Board

Report of the Marine Dissolved Oxygen Work Group

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April 19, 2017

Report of the Marine Dissolved Oxygen Work Group

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April 19, 2017

Executive Summary

The Department posed the following set of questions to the Science Advisory Board:

1. *To what extent is Dissolved Oxygen (DO) limiting to aquatic life in New Jersey's marine waters?*

2. *What species are at risk?*

3. *Gather data and review science, and determine what other States and the Federal government are doing to address DO?*

Department staff provided the SAB with an overview of its activities relative to these questions. In general, the Department found that most of New Jersey's ocean bottom waters often did not meet the State's current surface water quality criteria for dissolved oxygen, but the benthic community did not appear to be impacted. Estuarine waters were characterized by lesser but fluctuating impairment relative to criteria. The SAB considered the information presented by Department staff, and also conducted its own independent literature research on the topic.

With regard to Question 1, the SAB concludes that it is premature to arrive at a definitive and final response based on the NJ specific data presented. The SAB recommends that the Department consider further assessment of its substantive NJ specific information, and revisit this question at a later time. Further basis for this is provided in the response to questions 2 and 3 below.

With regard to Question 2, the SAB finds that, based on the general scientific literature, many species typical of NJ marine waters are at risk of sublethal effects when concentrations begin to fall below approximately 5 mgl^{-1}. Work funded by the Department concluded that the benthic macroinvertebrate community in NJ coastal waters was not impaired. This conclusion was based on the presence and numbers of organisms. However, this conclusion did not consider whether (a) those organisms were experiencing sublethal physiological, behavioral or reproductive effects, or (b) the presence of these organisms was a result of regular or even irregular influx of unimpaired organisms from waters outside the NJ coastal region.

With regard to Question 3, the SAB reviewed Federal and Atlantic coastal States DO criteria applicable to marine waters, and find them to be generally consistent with NJ's current DO criteria for such waters. The SAB also concludes that NJ's marine DO criteria are consistent with the scientific literature the SAB has reviewed in connection with question 2 above.

The SAB concludes that it would be premature to revise the current marine DO criteria until analysis of the extensive database assembled by the Department over more than 20 years is completed. But, even then the Department may not have a sufficient basis to revise its criteria without biological assessment data that evaluates sublethal effects of low DO. NJ's current marine DO criteria are consistent with the SAB's evaluation of current relevant scientific literature considering impacts to aquatic life at lower levels of DO. The SAB strongly supports the Department's efforts to better understand the basic science regarding DO and impact to aquatic life.

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Nomenclature

BMC	Benthic Macroinvertebrate Community
DO	Dissolved Oxygen
mgl^{-1}	milligrams per liter, also expressed as mg/l, which for most aquatic systems is equivalent to parts per million (ppm)
NJ	New Jersey
NYDEC	New York State Department of Environmental Conservation
SAB	NJDEP's Science Advisory Board
SC	the general surface water classification applied to coastal saline waters
SE	the general surface water classification applied to saline waters of estuaries
USEPA	United States Environmental Protection Agency

I. Background

Oxygen is essential to aquatic life. It exists in aquatic systems as a dissolved gas entering or exiting a waterbody at its free surface. The direction of movement ("into" versus "out of" a waterbody) depends on whether the actual concentration of oxygen in the waterbody at a specific time is greater than or less than the concentration that would exist when the waterbody is at equilibrium with the amount of oxygen in the overlying atmosphere. When the concentration of oxygen in a waterbody is in equilibrium with the concentration of oxygen in the overlying atmosphere, the dissolved oxygen in the waterbody is said to be at its saturation concentration. The dissolved oxygen saturation concentration for any particular waterbody is a function of several factors such as temperature and the partial pressure of oxygen in the atmosphere overlying the waterbody. Dissolved oxygen concentration is often expressed in units of milligrams per liter (mg/l or mgl^{-1}) which for most aquatic systems is equivalent to parts per million (ppm). For marine waterbodies in New Jersey, the typical dissolved oxygen saturation concentration is in the range of 7 to 10 mgl^{-1}.

Oxygen is (a) consumed in a waterbody by organisms as they digest organic matter, and (b) produced by plants as they harness the energy of sunlight to produce new biomass, i.e., the process of photosynthesis. There is a constant interplay between oxygen consumption, production, and transport across the water surface that determines the concentration of oxygen in a waterbody at any point in time.

The concentration of dissolved oxygen is arguably the single most widely used indicator of water quality in aquatic systems. Healthy aquatic systems tend to have oxygen concentrations at or around the saturation concentration. Waterbodies that have been enriched with organic matter (e.g., sewage) or have excess nutrients which stimulate algal blooms often have low concentrations of dissolved oxygen. The concentration of oxygen in a waterbody may vary laterally and vertically depending on mixing characteristics and other factors. When vertical mixing is weak a condition known as stratification occurs. In such conditions, oxygen levels are lower in the bottom waters because oxygen is consumed due to microbial degradation of organic matter in or near the bottom sediments, and higher in the upper waters near the surface where it is replenished from the atmosphere, photosynthesis and lower rates of microbial degradation of organic matter.

A. Charge to the Science Advisory Board

The Department posed the following set of questions to the Science Advisory Board:

1. *To what extent is Dissolved Oxygen (DO) limiting to aquatic life in New Jersey's marine waters?*

2. *What species are at risk?*

3. *Gather data and review science, and determine what other States and the Federal government are doing to address DO?*

A work group of the SAB was formed to consider these questions. The work group originally consisted of Judith Weis, Michael Weinstein and Raymond Ferrara. Dr. Weinstein subsequently retired from the SAB, and soon thereafter Jonathan Kennen joined the work group.

B. New Jersey's Dissolved Oxygen Criteria for Marine Waters

The term "marine waters" in the Department's question refers to those waters along the coast and in estuaries of New Jersey that are considered saline. Saline waters are defined at N.J.A.C. 7:9B-1.4 as waters having salinities generally greater than 3.5 parts per thousand at mean high tide. N.J.A.C. 7:9B-1.4 further identifies two classes of saline waters: SC which is the general surface water classification applied to coastal saline waters, and SE which is the general surface water classification applied to saline waters of estuaries. There are three categories of SE waters, namely SE1, SE2, and SE3.

New Jersey's Surface Water Quality Criteria for DO are provided at N.J.A.C. 7:9B-1.14(d). SC and SE1 waters have the most stringent numeric criteria for DO followed respectively by SE2 and SE3 waters each of which have progressively less stringent numeric criteria for DO as follows:

- SC: DO not less than 5.0 mgl^{-1} at any time
- SE1: DO not less than 5.0 mgl^{-1} for 24 hour average; and DO not less than 4.0 mgl^{-1} at any time
- SE2: DO not less than 4.0 mgl^{-1} at any time
- SE3: DO not less than 3.0 mgl^{-1} at any time

There are very few waters of NJ that are classified SE2 or SE3 (i.e., almost all estuarine waters are SE1).

C. A Summary of Work Conducted by the Department

The Department has been considering the above questions long before they were posed to the SAB. Consequently, the Department has undertaken a variety of activities that provide useful information. An overview of those activities was presented to the Work Group in meetings and in a summary document entitled "*Overview of the Department's Work to Date regarding the DO of the saline coastal and estuarine waters in New Jersey, Prepared for the SAB Working Group – Marine Dissolved Oxygen Charge Question*". The most recent version of that summary document is dated July 2016, and is included herein as Appendix A. It will hereafter be referred to as the Department's 2016 Summary Document. Highlights from the 2016 Summary Document are as follows: (Page numbers cited below are those in the 2016 Summary Document.)

- Data collected by USEPA in the 1990s revealed that 70% of New Jersey's ocean bottom waters did not meet the State's surface water quality criterion. (p. 3)

- USEPA helicopter DO surveys were conducted between 1979 and 2005 for the coastal waters between Sandy Hook and Cape May. Surface and bottom samples were collected 1979 to 1997. Only bottom samples were collected 1997 to 2005. These data showed that surface samples were generally good, but bottom samples fell below the criteria during the summer in every year. These data suggested strong vertical stratification. (p.4)

- Starting in 2011, Slocum gliders were employed to measure DO in NJ coastal waters from Sandy Hook to Cape May during June through October. (p. 6) While the 2016 Summary Document discusses some of the data findings, it notes that "Further assessment of the data from all years will be performed" (p. 9), and "data analysis of the collected Slocum glider data is ongoing". (p. 10) It is the Work Group's understanding that this data analysis is ongoing, albeit at a limited pace.

- In comparison to coastal waters, data collected in estuarine waters (1998 to 2012) revealed lesser but fluctuating impairment. (See Figure 1 from the 2016 Summary Document.)

  - These data are reported as having been collected between 7 am and 11 am on each date of sampling, and hence may not represent the minimum DO concentrations that occur at or just before sunrise at these sampling sites. (pp. 3 and 10)

  - Later estuarine DO data (2013 to 2015) "is currently being processed and results are not yet available." (p. 10)

  - Barnegat Bay DO data are specifically discussed in the 2016 Summary Document. Results were quite good for the fixed station grab sampling with very few instances where DO was less than the criterion of 4 mgl^{-1} (p. 10) But it is noted that these samples were collected between 7 am and 11 am and again may not have captured the minimum DO concentrations that occur in the early morning hours at or just before sunrise. The Department augmented the sampling with four continuous monitoring buoys located throughout Barnegat Bay to measure diurnal changes in dissolved oxygen. (p. 11) The sensors on these buoys were located about mid-depth. It was noted that Barnegat Bay is shallow and vertically mixed; consequently a mid-depth sample would be representative of the entire depth at a sampling site. Data collected between May and November 2012 indicate very few instances where DO was observed below 4 mgl^{-1}, except for the mouth of the Toms River.

- Rutgers (Ramey et al., 2011) was contracted to conduct a study to determine if the low DO levels observed in the coastal waters were impacting the benthic community. (p. 11) Sampling was conducted in 2007, 2009 and 2010. The study found:

  - Whether and the degree to which stratification occurred from year to year varied greatly. (p. 12)

- o During 2010 when stratification was not present, ocean outfalls from wastewater treatment plants did not adversely impact DO. (p. 12)

- o Benthic macroinvertebrate sampling indicated 28% of stations were “unpolluted”, and 72% of stations were “slightly polluted”. (p. 12) These determinations were reviewed and assessed by a panel of national experts.

- o Species composition, distribution and abundance were primarily influenced by natural factors rather than pollution. (p.13)

- o A DO criterion of 5 mgl^{-1} is well above the level expected to have a severe impact on benthic communities. (p. 13)

- o The benthic index developed in the study must be further calibrated and validated. (p. 13)

In general, the findings of this study were quite favorable in regard to the quality of the benthic community in NJ’s coastal waters. The national panel of experts concluded that the benthic community of NJ’s coastal waters were not impaired.

- In 2011, Rutgers University (Taghon et al., 2015) was contracted to conduct a study to evaluate the benthic community in Barnegat Bay. (pp. 11 through 14) Sampling was conducted in July for years 2012 to 2014. (p. 13) That study found:

  - o Bottom DO varied between 2.1 and 10.4 mgl^{-1} with no apparent spatial pattern. (p. 13)

  - o The benthic community was dominated by very few species, and many of them were characteristic of unimpacted estuarine conditions. (p. 14)

  - o The benthic community was classified as: (p.14)
    - Poor at 1 station
    - Moderate at 10 stations
    - Good at 80 stations
    - High at 6 stations
    - The average was good in all three years.

  - o During this 2011 study, DO sampling and benthic macroinvertebrate sampling were not conducted at the same locations, but more recently the Department has coordinated such sampling. Although all of the DO sampling completed in this study was not conducted at the critical time (i.e., pre-dawn), as noted above, the Department has undertaken continuous DO monitoring at four locations in the Bay.

II. Recommendations Regarding Charge Questions

A. ***Question 1:*** To what extent is Dissolved Oxygen (DO) limiting to aquatic life in New Jersey's marine waters?

Finding:

The SAB concludes that it is premature to arrive at a definitive and final response to Question 1 based on the NJ specific data presented. The SAB recommends that the Department consider further assessment of its substantive NJ specific information, and revisit this question at a later time. However, this question is further explored through generally available information in the scientific literature in response to Questions 2 and 3.

Discussion:

The Department has undertaken a substantial effort to evaluate whether the health of the coastal benthic macroinvertebrate community has been compromised as a consequence of DO levels. The expert panel employed by the Department concluded that the coastal benthic macroinvertebrate community is not impaired. However, that work seems to draw conclusions about the general health of the benthic community, and does not focus specifically on DO effects. That work suggests that the benthic macroinvertebrate community is not adversely impacted, and therefore by inference DO levels must be sufficient to support a healthy benthic macroinvertebrate community. Department staff have pointed out that DO is an indicator of potential biological impairment, and indeed it is. They further assert that if the benthic community has not been observed to be impaired, then one could assume that DO, along with a number of other factors has not had a negative impact.

The Department's 2016 Summary Document has stated that DO levels in coastal bottom waters (1979 to 2005) have historically been below NJ's current DO criteria for these waters, suggesting that the current DO criteria are unnecessarily stringent. But, we note that the cited DO data are from 1979 – 2005, yet the BMC data are from 2011.[1] Hence the data are not synoptic. The SAB suggests that the Department consider a thorough evaluation of the historical and more recent Slocum glider DO data. Evaluation of the Slocum glider data along with the USEPA helicopter data will surround (in time) the benthic macroinvertebrate community data, and may resolve this concern.

The SAB further notes that while benthic macroinvertebrate community information is certainly useful, a thorough assessment of DO effects must consider fish as well. The Department has not presented information regard the latter.

Given the above, the SAB concludes that it is premature to arrive at a definitive and final response to Question 1 based on the NJ specific data available for the following reasons:[2]

[1] Department staff have asserted that DO measurements were taken with each benthic sample at 1 meter profiles with no adverse impact noted. The SAB has not been provided those data or that demonstration.
[2] Generally available scientific literature will be discussed further in response to Questions 2 and 3 below.

1. With regard to coastal waters, a complete and thorough analysis and presentation of the more recent Slocum glider data should be conducted. Such a presentation could be valuable as a tool to compare against the historical USEPA helicopter survey data and the Rutgers benthic macroinvertebrate community data. Upon completion of that assessment the Department may have a basis for drawing conclusions about coastal DO levels and the benthic macroinvertebrate community. But, the SAB emphasizes the importance of having DO samples taken at the same time and location as biological samples. Furthermore, since fish data are not available, deriving conclusions about observed DO levels and the fish community will not be possible.

2. With regard to the estuarine environment, the only NJ site specific DO data that have been presented to the SAB are those for Barnegat Bay. These data cannot serve as a basis for answering Question 1 statewide. The Department has historical estuarine data throughout the state (1998 – 2012), but virtually no presentation of this information has been provided. Furthermore, the Department has more recent estuarine data (2013 to 2015), but as yet has not processed or analyzed it. The SAB believes that compilation and evaluation of all of these estuarine DO data may enable a more substantive response to Question 1 for estuarine waters. But again we caution that the lack of estuarine data during critical pre-dawn times may impede the development of defensible conclusions.

B. ***Question 2:*** **What species are at risk?**

Finding:

The SAB finds that, based on the general scientific literature, many species typical of NJ marine waters are at risk of sublethal effects when DO levels begin to fall below approximately 5 mgl^{-1}. Specific species are identified below, and include gastropods, amphipods, dogfish, silversides, summer flounder, grass shrimp, crab and sturgeon. Ramey et al. (2011) as cited above in Section I.C concluded that the benthic macroinvertebrate community in NJ coastal waters was not impaired. But this conclusion was based on the presence and numbers of organisms. However, this conclusion did not consider whether (a) those organisms were experiencing sublethal physiological, behavioral or reproductive effects, or (b) the presence of these organisms was a result of regular or even irregular influx of unimpaired organisms from waters outside the NJ coastal region.

Discussion:

Understanding the risk of low DO levels to marine and estuarine species in New Jersey coastal waters requires a rigorous evaluation of individual stress levels (via hypothesis testing) associated with life-history traits, and an understanding of the uncertainty associated with Type I and Type II error. Managers and decision makers cannot operate based on cultural, socioeconomic or societal perspectives, nor can they rely on a purely theoretic point of view (i.e., best professional judgement). They need information on the susceptibility of species to stressors such as low DO, and this understanding can only be accomplished through the scientific method, which is time consuming. There are probably thousands of species that are at risk, but we are uncertain about their level of risk because they have not been examined. The List of Fishes of NJ marine and estuarine waters is extensive (see Appendix B), but only a few of these have actually been studied and found to be sensitive to low DO, e.g., silversides, dogfish, and summer and winter flounder. There have, however, been a number of studies evaluating the sublethal effects on species that live in NJ estuarine and marine environments or congeneric (same genus) species that live elsewhere. Below is the SAB's review of the available literature on the effects of low DO on marine and estuarine organisms relevant to NJ coastal waters.

Studies have assessed the effects of low DO on a variety of marine and estuarine organisms including crustaceans, mollusks and fish. In some species, effects are seen at DO levels in the 3.0 to 4.5 mgl^{-1} range, well above what is usually considered "hypoxic."[3]

Sublethal effects that have been observed include physiological effects, such as reduced respiration, reduced feeding, reduced activity (lethargy), clearance rate, scope for growth, and energy balance. Some species living in low DO waters were found to switch to the glycolytic pathway, which is considered to be an energy-conversion pathway in many organisms that live in stressed environments. Early life stages tend to be more susceptible to DO effects. Reproductive and developmental effects that have been seen in many taxa include reduced fertility and fertilization, reduced embryo development, delayed hatching, reduced larval growth and survival, reduced metamorphosis of larvae, and reduced feeding and growth rates of juveniles and adults. Behavioral effects include reduced feeding (which is very common and can account for the frequently observed reduced growth), reduced burrowing in benthic species (which makes them more susceptible to predators in the water column), emersion from the water in crustaceans, reduced anti-predator responses, and reduced spawning behavior in a variety of taxa including some from the mid-Atlantic. Ecosystem level effects have also been seen, but generally in hypoxic (<3 mgl^{-1}) waters (Appendix C).

It should be noted that the laboratory studies of low DO did not include altered (reduced) pH. In coastal waters and estuaries, low DO commonly results from bacterial respiration during decomposition, and therefore is accompanied by increased CO_2 which causes increased acidity. This continuously dynamic chemical reaction is documented in detail in the SAB Report on Ocean Acidification by Weis, Kennen, and Vaccari (2015). Reduced pH could potentially exacerbate the effect of low DO because the effects produced by a given level of DO in a laboratory study could translate to a higher level of stress in the field where the pH is lower. Furthermore, studies on the combined effects of low DO, increased temperature and increased acidification, which tend to occur together, show that detrimental effects of DO are intensified when temperature is higher and acidification is greater (Baumann et al. 2016; DePasquale et al 2015). This combination is a condition commonly found in New Jersey coastal waters.

Respiration

A general response to low DO is reduced respiration and activity. Liu et al. (2011) found that larval respiration rates of the gastropods *Nassarius siquijorensis* and *N. conoidalis* were reduced at 4.5 mgl^{-1} and swimming speed was reduced in 10-day old larvae exposed to <2.0 mgl^{-1} for *N. siquijorensis* and <1.0 mgl^{-1} for *N. conoidalis,* indicating that the latter species is more tolerant of low oxygen conditions. (*N. obsoletus* is common in NJ).

[3] The USEPA DO criteria document considers "hypoxia" to be any condition where the concentration of DO is below the saturation concentration. Our definition of hypoxia is the more customary condition where DO levels are substantially below the saturation concentration (e.g., less than 3 mgl^{-1}).

Juvenile turbot *Scophthalmus maximus* were fed to satiation at reduced DO concentrations of 3.5, 5.0 and 7.2 mgl^{-1} (normoxia). Both feed intake and growth rate were significantly lower under hypoxic conditions. Oxygen consumption of feeding fish was significantly higher under normoxia, but following 7 days of feed deprivation, oxygen consumption was similar under normoxia and hypoxia (Pichavant et al. 2000).

The activities of glycolytic enzymes in liver and skeletal muscle were determined in mummichogs, *Fundulus heteroclitus* prior to the onset of low DO treatments (1 mg l^{-1} for severe hypoxia, 3 mgl^{-1} for moderate hypoxia), and at intervals thereafter (Abbaraju and Rees, 2012). Significant effects of low DO were seen on three liver enzymes, whose specific activities were highest in fish in severe hypoxia, especially after 14 days. In skeletal muscle, only one glycolytic enzyme was affected, and it was found to be significantly lower in fish in severe hypoxia than in those at moderate hypoxia at 14 d. These observations may indicate that mechanisms causing these alterations are enzyme- and tissue- specific, rather than applying uniformly to all enzymes in the glycolytic pathway.

Reproduction and Development

A study by Wu and Or (2005) indicated that reproduction in the amphipod *Melita longidactyla* was impaired by moderate DO levels (3.5 to 4.5 mgl^{-1}), which is higher than levels considered to be hypoxic (i.e., 2.8 mgl^{-1}). Negative growth and decreases in respiratory energy expenditure were noted after exposure to moderately low DO for 3 weeks. Complete reproductive failure occurred after exposure to 3.5 mgl^{-1} for 1 month, but no significant effect was seen at 4.5 mgl^{-1}, indicating that reproductive impairment occurs below 4.5 mgl^{-1} (Wu and Or, 2005). (*M. nitida* is a common component of the NJ benthic community).

Energy exchange between yolk and embryo in dogfish (*Scyliorhinus canicula)* eggs in 100%, 50% and 20% saturation, and anoxia for 2 hr/day was studied for 10 weeks, starting when eggs were 13–15 weeks old (Diez and Davenport, 1990). Exposure to 20% saturation was lethal after 3 weeks; eggs exposed to anoxia for only 2 hr/day died after 10 weeks. Animals in normoxia and 50% saturation (4 ppm) survived, but those in reduced DO had reduced growth. (*S. retifer*, the chain dogfish, is a congeneric species of dogfish that lives in NJ coastal waters).
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The embryo/larval development of bay scallop (A*rgopecten irradians*) was inhibited at a DO of 1.38–3.64 mgl^{-1} at 23°C (Wang and Zhang, 1995). Tolerance to anoxia increased with larval sizes and was related to their oxygen debt (accumulation of lactic acid). Gastropod larvae may be more sensitive than the bivalves. For example, the effects of low DO on early development and swimming behavior of veliger larvae of the snail, *Nassarius festivus* were studied by Chan et al. (2008) who found that embryonic development was significantly delayed when DO was reduced to 3.0 mgl^{-1} *(N. obsoletus* is a common congeneric species that lives in NJ waters). Veligers that hatched at 4.5 mgl^{-1} had smaller lobes, reduced shell length and width, and slower swimming speeds than those in normoxia. The percentage that developed into juveniles was reduced and metamorphosis was delayed at 4.5 mgl^{-1} while all larvae at 3.5 mgl^{-1} died before metamorphosis. Juveniles that developed at 4.5 mgl^{-1} were smaller than those at 6.0 mgl^{-1}, indicating that even DO levels well above hypoxic levels (i.e., 2.8 mgl^{-1}) can significantly impair hatching and larval development success rates in these gastropods.

Eggs, larvae and juvenile life stages of Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) appear to be highly sensitive to low DO. As part of a recent study by The Nature Conservancy (2016) evaluating the potential impacts of DO levels on Atlantic sturgeon in the Delaware River, a relationship between juvenile recruitment and DO was identified. During years when recruitment was observed, minimum daily DO was above 5.0 mgl^{-1} in 90% of the observations, and the median minimum daily DO was > 6.0 mgl^{-1} during the spawning and egg and larval development periods). During years when recruitment was not observed, median minimum daily DO was between 4.0 and 5.0 mgl^{-1}, and conditions were frequently < 4.0 mgl^{-1}. (The Nature Conservancy 2016).

Steirhoff et al. (2006) found that growth rates of winter flounder *Pseudopleuronectes americanus* and summer flounder *Paralichthys dentatus* were reduced as DO decreased, particularly at 50-70% saturation, and as temperature increased. Summer flounder tended to be more tolerant than winter flounder of low DO levels. A significant relationship between feeding and growth rate indicated that reduced food consumption at low DO levels was responsible for the growth limitation. In a related study, Poucher and Coiro (1997) found that reduced growth rates for embryo through larva of Atlantic silversides (*Menidia menidia*) occurred at 4.3 mgl^{-1} and at 3.5 mgl^{-1} for newly metamorphosed summer flounder. They also found that growth of juvenile striped bass was reduced at low DO at high temperatures typical of surface waters during summer than in cooler water, and growth of plaice and dab was reduced at 4.1 to 2.5 mgl^{-1} at 15^{o}C.

In California, analysis of the sensitivity of species in Suisan Bay (near San Francisco Bay) to changes in DO was performed. The most sensitive endpoints for chronic DO effects were associated with the amphipod (*C. volulator*; 4.0 mgl^{-1}), silversides (*M. menidia*; 4.33 mgl^{-1}), summer flounder (*P. dentatus*; 4.52 mgl^{-1}), mud crab (*D. sayi*; 4.63 mgl^{-1}), grass shrimp (*P. vulgaris*; 4.67 mgl^{-1}) and sturgeon (*A. oxyrinchus*; 4.77 mgl^{-1}). The silversides, summer flounder, grass shrimp and sturgeon are all commonly found in NJ waters. All of these species appear to be sensitive to changes in DO levels, especially when DO drops below 5.0 mgl^{-1}, a level where chronic affects were observed. (For example see Bailey et al, Science Supporting Dissolved Oxygen Objectives for Suisun Marsh San Francisco Regional Water Quality Control Board, 2014.)

Behavior

Bell et al. (2003) used biotelemetry and measurements of DO to monitor the feeding and movements of the free-ranging blue crab *Callinectes sapidus* to episodic hypoxic events and subsequent relaxation events within the Neuse River Estuary, North Carolina. Although crabs did feed in water with DO as low as 1.01 mgl^{-1}, feeding declined in mild (2 to 4 mgl^{-1}) and severe hypoxia (<2 mgl^{-1}). The proportion of time crabs spent feeding during periods of hypoxia was greatly reduced. However, when DO increased, the proportion of time crabs spent feeding did not increase and crabs did not reinvade deeper water habitats, as had been hypothesized (*C. sapidus* is a widespread crab species that is found throughout NJ coastal and estuarine environments).

Effects of low DO in reducing fish growth discussed above (e.g., Steirhoff et al. 2006; Thetmeyer et al., 2001, Pichavant et al. 2000, 2001) were found to be largely due to reduced feeding. However, the negative effects of hypoxia on fish feeding behaviors can sometimes be compensated for by increased availability of benthic prey during periods of hypoxia. For example, in a field study, spot (*Leiostomus xanthurus*) and hogchoker (*Trinectes maculatus*) showed enhanced prey exploitation during or right after hypoxic events in Chesapeake Bay (Pihl et al.

1992). Predator-prey dynamics between the blue crab *C. sapidus* and an infaunal clam *Mya arenaria* were examined by Taylor and Eggleston (2000) to assess the impact of hypoxia upon foraging rates and prey mortality. Interactions were studied in normoxia, moderate hypoxia (3.0 to 4.0 mgl^{-1}) after acclimation to high DO, and moderate hypoxia after acclimation to low DO. This study found that clam burial depth decreased and siphon extension increased in hypoxic conditions. Additionally, low DO affected the interaction between *C. sapidus* and *M. arenaria* by either hindering blue crab foraging, or alternatively, increasing clam vulnerability to predation. Thus in areas where hypoxia is intermittent, its effect on behavior of macrobenthos may be advantageous to oxygen-tolerant bottom-feeding fish or crabs. However, in the Neuse River estuary, intermittent hypoxia negatively affected the feeding behavior of croakers, *M. undulatus* by restricting them to shallower oxygenated areas where prey were less abundant and by killing deeper benthic prey, thus greatly reducing their numbers (Eby et al. 2005).

Field studies in the Long Island Sound by Howell and Simpson (1994) examining adult fishes in trawl samples found that butterfish (*Peprilus tricanthus*), winter flounder (*Pleuronectes americanus*), and windowpane flounder (*Scophthalmus aquosus*) were less abundant when the DO was below 3.0. In these samples, winter flounder were also smaller when DO was below 3.0. They also stated that squid and bluefish were sensitive to low DO.

USEPA in their Water Quality Criteria Document present many data showing responses at DO levels of 4 to 5 mgl^{-1}. One example is the following table.

EPA Excerpt from Table 3 showing chronic ppm values for growth

Chronic value (mgl^{-1})	
Paralichthys dentatus summer flounder newly metamorphosed juvenile	2.81
Homarus americanus American lobster larval stage 2 to 3	4.59
Homarus americanus American lobster larval stage 2 to 3	4.30
Homarus americanus American lobster larval stage 3 to 4	6.48
Homarus americanus American lobster larval stage 3 to 4	4.32
Homarus americanus American lobster larval stage 3 to 4	4.71
Homarus americanus American lobster postlarval stage 4 to 5	5.09
Homarus americanus American lobster juvenile stage 5	5.19
Dyspanopeus sayi Say mud crab larval stage 1 to 3	2.85
Dyspanopeus sayi Say mud crab larval stage 1 to 3	3.96
Dyspanopeus sayi Say mud crab larval stage 3 to 4	5.60
Dyspanopeus sayi Say mud crab larval stage 3 to megalopa	4.89
Dyspanopeus sayi Say mud crab larval stage 3 to megalopa	5.20
Dyspanopeus sayi Say mud crab larval stage 3 to megalopa	4.91
Dyspanopeus sayi Say mud crab larval stage 3 to megalopa	4.93

Based on the above literature review, it is difficult to reconcile the Department's findings that the benthic macroinvertebrate community is not impaired in NJ coastal waters that have low DO (see Ramey et al. 2011 as cited above in Section I.C). There are a number of potential explanations for these seemingly contradictory findings.

1. The polychaete worms that comprise the majority of the sampled benthic infauna are not among the species that appear in this literature review, and these taxa are known to be highly tolerant of low DO.
2. While many polychaete worms are tolerant of low DO levels, this does not necessarily mean that they are not impaired physiologically, developmentally or behaviorally at low DO. To properly understand the effects of low DO on their health, live individuals would have to be studied in the laboratory so that any changes in life history and behavior associated with low DO can be compared to those from unstressed areas.
3. It is possible that many members of the benthic community sampled were reproductively impaired, but the community was sustained by a continual influx of larvae from locations where successful reproduction occurs. This possibility should be investigated.
4. It may be that populations living in chronically low DO conditions have become more tolerant of low DO by either physiological acclimation (a process by which an individual organism adjusts to a gradual change in its environment) or genetic adaptation. This could be tested by comparing their tolerance with that of the same species collected from areas without low DO.

If polychaetes or other benthic fauna were found to have adjusted to low DO by developing enhanced tolerance, that finding would not, in itself, justify changing the DO criterion since populations that are tolerant to one stressor are frequently less tolerant to other stressors (i.e., “no free lunch”). For example, mussels, *Perna viridis* from impacted Jakarta Bay (Indonesia) are more tolerant to low DO than those from reference sites. But they were less resistant to low salinity (Huhn et al. 2016). Populations that have become tolerant to a stressor have also been found to be less fit compared with non-tolerant populations without the stressor. For example, Levinton et al. (2003) investigated a Cd-tolerant population of the oligochaete *Limnodrilus hoffmeisteri* in Foundry Cove, a highly Cd-contaminated site in the Hudson River. After this Superfund site was cleaned up, there was a rapid loss of tolerance within less than a decade (Levinton et al. 2003).

The discussion in Ramey et al. (2011, pp. 57 and 58) indicates that at the times and places that the benthic samples were taken, the benthic community was found to be healthy, but the DO was high at around 5.0 mg L^{-1}. “Concentrations in 2007 were well above the suggested critical values (x = 6.2 mgl^{-1} ±0.24 CI), while concentrations were lower in 2009 (x = 4.9 mgl^{-1} ±0.45 CI)”. Therefore, it appears that the findings of the Ramey et al. report are not contradictory to the critical DO values established in the literature for many nearshore benthic organisms, especially those for 2007.

Additionally, a recent paper by Hrycik et al. (2016) using a structured meta-analysis of published studies, found significant negative effects of DO on fish growth and consumption below 4.5 mgl^{-1}. This finding is consistent with the above literature which indicates that DO levels at or below 5 mgl^{-1} is limiting to aquatic life in New Jersey’s marine waters.

C. ***Question 3:*** **Gather data and review science, and determine what other States and the Federal government are doing to address DO?**

Finding:

The SAB has reviewed the Federal DO criteria applicable to marine waters, as well as various Atlantic coastal States DO criteria for marine waters, and find them to be generally consistent with NJ's current DO criteria for marine waters. We also conclude that NJ's marine DO criteria are consistent with the scientific literature the SAB has reviewed as cited in our response to Question 2.

Discussion:

The USEPA provides recommendations for DO criteria in its November 2000 criteria document.[4] That document suggests the following:

- chronic (>24 hours) DO levels should not fall below 2.3 mgl^{-1} to protect against impacts to juvenile and adult aquatic life survival
- chronic (>24 hours) DO levels should not fall below 4.8 mgl^{-1} to protect against impacts to juvenile and adult aquatic life growth effects
- a complicated recommendation regarding site specific duration and intensity of hypoxia regarding protection against effects to larval recruitment (the SAB does not recommend adoption of this approach for NJ waters)
- equations to evaluate allowable DO levels for short term exposure (i.e., allowable DO concentration is a function of intensity and duration of exposure)

The above chronic criterion to protect against growth effects is similar to NJ's SC and SE1 criteria. And they are supported by the scientific literature cited in response to Question 2.

The State of New York has effectively adopted the criteria in the USEPA criteria document discussed above. (NYDEC 2008)

The State of Pennsylvania does not prescribe DO criteria for marine waters.

The State of Delaware prescribes that for marine waters, the daily average DO shall not be less than 5.0 mgl^{-1}, and the instantaneous minimum shall not be less than 4.0 mgl^{-1}. These levels are identical to NJ's SE1 criteria, and slightly less stringent than NJ's SC criterion.

[4] USEPA Office of Water, *Ambient Aquatic Life Water Quality Criteria for Dissolved Oxygen (Saltwater): Cape Cod to Cape Hatteras*, EPA-822-R-00-012, November 2000

Florida has recently published a basis for DO criteria.[5] They chose to express the DO criteria for marine waters as percent of saturation, and concluded the following:

- The daily average percent DO saturation shall not be below 42 percent in more than 10 % of the values, and

- The weekly and monthly average percent DO saturations shall not be below 51 and 56 percent, respectively

Consequently, the actual DO concentration that must be provided on any given day will vary with temperature which of course varies throughout the year. The SAB questions the validity of applying such an approach to NJ or any other waters. Organisms are sensitive to actual DO concentration, not % saturation of DO. Furthermore, organisms respire more rapidly at higher temperatures and hence DO availability becomes more critical at higher temperatures. Consequently, at higher temperatures, the saturation concentration of DO is lower. Hence, expressing a criterion as a % of saturation prescribes lower actual DO levels at higher temperature than at lower temperature, and therefore, such a criterion allows lower DO concentration during the more critical times when organisms need more DO.

[5] Florida Department of Environmental Protection, *Technical Support Document: Derivation of Dissolved Oxygen Criteria to Protect Aquatic Life in Florida's Fresh and Marine Waters*, DEP-SAS-001/13, March 2013

III. Conclusion

In our discussions with Department staff, it appeared that they were considering that the current marine DO criteria may be too restrictive because (a) prior assessments have concluded that DO levels are below the current criteria in NJ coastal waters, and (b) adverse impacts to the benthic macroinvertebrate community have not been observed at those levels of DO. The SAB's opinion is that additional work, including analysis of the extensive database assembled by the Department over more than 20 years, might eventually provide NJ specific information that could possibly support revision to the current marine DO criteria. However, until those analyses are completed, it would be premature to revise the current marine DO criteria.

We also believe that the current database may need to be augmented with biological assessment data to evaluate sublethal effects of low DO. The extensive scientific literature that the SAB has reviewed and reported here indicates that sublethal effects in a wide variety of species begin at about the levels identified in NJ's current marine DO criteria. Furthermore, NJ's current marine DO criteria are similar to those promoted by USEPA in its DO criteria document which New York has effectively adopted. Marine DO criteria for other states are similar to New Jersey's.

We believe that the Department has undertaken an extremely worthwhile exercise in evaluating the effects of DO in marine waters. The SAB complements the Departments capacity to implement a 5.0 mgl^{-1} criteria because that threshold is strongly supported by our evaluation of the literature which includes a very timely meta-analysis of fish response to DO by Hrycik et al. (2016) that consistently showed negative effects below 4.5 mgl^{-1}. The SAB strongly supports the Department's efforts to better understand the basic science regarding DO and impact to aquatic life.

APPENDIX A

New Jersey Department of Environmental Protection, “Overview of the Department’s Work to Date regarding the DO of the saline coastal and estuarine waters in New Jersey, Prepared for the SAB Working Group – Marine Dissolved Oxygen Charge Question”, July 2016

Overview of the Department's Work to Date regarding the dissolved oxygen of the saline coastal and estuarine waters in New Jersey

Prepared for the SAB Working Group - Marine Dissolved Oxygen Charge Question

Prepared by

New Jersey Department of Environmental Protection

July 2016

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Introduction

This document provides a summary of the work to date undertaken by New Jersey DEP with regard to dissolved oxygen (DO) in coastal and estuarine NJ waters. The document is comprised of three sections: 1) a brief description of DO standards for saline waters and the designated impairments found in New Jersey, 2) a summary of available DO data collected since 1979, and 3) results from ocean and Barnegat Bay studies on benthic invertebrates.

New Jersey's ocean waters are currently listed as impaired in the Integrated Report (http://www.nj.gov/dep/wms/bears/docs/2012_integrated_report.pdf) based on the failure to meet the New Jersey water quality standard of not less than 5 mg/l at any time in the bottom waters of Coastal Saline Waters (SC). The Department (NJDEP) performed an evaluation of the ocean water bottom dissolved oxygen data, from discrete samples collected from the USEPA Helicopter flights between 1979 and 2005. Data shows that low dissolved oxygen conditions, less than 5mg/l, occurred every year during the summer sampling period, and that almost every year experienced DO levels below 2 mg/l. The NJ coastal waters were listed on 303(d) by the USEPA in the 1990's and there was an assumption that although there is a predisposition for these waters to have depressed dissolved oxygen due to warm weather stratification, these low dissolved oxygen sags were exacerbated by the biochemical oxygen demand (BOD) effect from the nutrient rich NY/Raritan plume emanating through the Bight and out from the New Jersey coastal outlets.

The 2012 Integrated Report also provides a list of estuarine waters impairments. Estuarine waters have different criteria in function of water type as defined by NJDEP (Table 1). Examples of estuarine FW2-NT and SE1 waters listed for DO impairment include Poricy Bk/Swimming R and Navesink R (below Rt 35)/LowerShrewsbury and SE1 waters in Branchport Creek.

To better assess oxygen conditions in the ocean, in 2011 the USEPA, Rutgers University, and NJDEP started to routinely use a Slocum glider to measure dissolved oxygen from Sandy Hook to Cape May, from surface water to bottom, collecting data at 1 second intervals. Rutgers University evaluated the early data, and hypothesized that low oxygen may be a natural condition off the New Jersey Coast due to prevailing meteorological conditions during the summer months causing stratification of the water column. The prolonged summer stratification results in a poorly mixed bottom layer with consistently low oxygen concentrations. Evaluation of the Slocum glider data shows that the dissolved oxygen conditions can vary greatly in spatial extent and duration and also confirms low DO concentrations during the summer.

A three-year study (2007, 2009 and 2010) based on benthic macroinvertebrates was undertaken by Rutgers through a NJDEP contract to study benthic species composition and their response to water DO levels, and to develop an index to characterize the biological health of the ocean. Benthic invertebrates were used as indicators because of their inability to move away from low oxygen events the way most fish do. Water column measurements at one (1) meter increments were taken for dissolved oxygen, pH, salinity, and temperature. Sampling for the benthic invertebrates was also conducted in 2013, for which the results are pending. Results from the three-year study indicated that the ocean macroinvertebrate populations were overall in good health and did not appear to be negatively impacted by low DO concentrations; however, this assessment did not include the finfish populations, which would require additional work. This study also showed no relationship between the biological condition and the influence of upwelling nodes, regions along the ocean floor believed to be under the influence of periodic low dissolved oxygen. Work is currently ongoing to evaluate the applicability of the macroinvertebrate index for routine assessment purposes. An additional study was conducted in Barnegat Bay in 2012-2014 based on benthic invertebrate fauna to assess the Bay's condition. This study revealed that bottom water DO varied between 2.1-10.4 mg/L and that overall the Barnegat Bay benthic invertebrate community was in good condition over the 3-year study period.

Section 1: Dissolved Oxygen Standards and Designated Impairments

The current New Jersey Water Quality Standards, found at N.J.A.C. 7:9B, lists the ten classifications of surface waters that are used to assign a numeric water quality standard that is intended to protect those designated uses of that water body. For saline waters, there are five classifications that include three for saline estuarine waters and two for ocean waters (SE1, SE2, SE3, SC and FW2-NT/SE1). FW2-NT/SE1 means a waterway in which there may be a salt water/fresh water interface. These water bodies can be designated as "impaired" if they fall outside the desirable boundaries set by the corresponding water quality standard. Currently, the State of New Jersey uses a single numeric value for which the level of dissolved oxygen cannot fall below for all saline waters. Table 1 provides the three most common classifications, the designated uses of those classifications and the related numeric criteria for dissolved oxygen that is set to protect those designated uses (refer to N.J.A.C. 7:9B for more details).

Table 1: New Jersey Surface Water Classifications, uses and DO criteria

Classification	Name	Uses	Criteria
FW2-NT	Interface freshwater/saline estuarine water	☐ Maintenance, migration and propagation of the natural and established biota; ☐ Primary contact recreation; ☐ Industrial and agricultural water supply; ☐ Public potable water supply after conventional filtration treatment (a series of processes including filtration, flocculation, coagulation, and sedimentation, resulting in substantial particulate removal but no consistent removal of chemical constituents) and disinfection; and ☐ Any other reasonable uses.	24 hour average not less than 5.0, but not less than 4.0 at any time Supersaturated dissolved oxygen values shall be expressed as their corresponding 100 percent saturation values for purposes of calculating 24 hour averages

Classification	Name	Uses	Criteria
SE1	Saline Estuarine Waters	• Shellfish harvesting in accordance with N.J.A.C. 7:12; • Maintenance, migration and propagation of the natural and established biota; • Primary contact recreation • Any other reasonable uses	24 hour average not less than 5.0, but not less than 4.0 at any time Supersaturated dissolved oxygen values shall be expressed as their corresponding 100 percent saturation values for purposes of calculating 24 hour averages
SE2	Saline Estuarine Waters	• Maintenance, migration and propagation of the natural and established biota • Migration of diadromous fish • Maintenance of wildlife • Secondary contact recreation • Any other reasonable uses	Not less than 4.0 mg/L at any time.
SE3	Saline Estuarine Waters	• Secondary contact recreation • Maintenance and migration of fish populations • Migration of diadromous fish • Maintenance of wildlife • Any other reasonable uses	Not less than 3.0 mg/L at any time.
SC	Saline Coastal Waters	• Shellfish harvesting • Primary contact recreation • Maintenance, migration and propagation of the natural and established biota • Any other reasonable uses	Not less than 5.0 mg/L at any time.

Data collected by USEPA in the 1990s revealed that 70% of New Jersey's ocean waters (bottom waters) did not meet the State's surface water quality criterion.

Data assessed for the estuarine waters (1998-2012) indicated that impairment of these waters have fluctuated over the years (Figure 1). Water samples collected for this evaluation were collected between 7 am and 11 am. Samples collected in this time frame are not expected to include the minimum dissolved oxygen concentration, which is expected to occur during the very early morning hours, before sunrise.

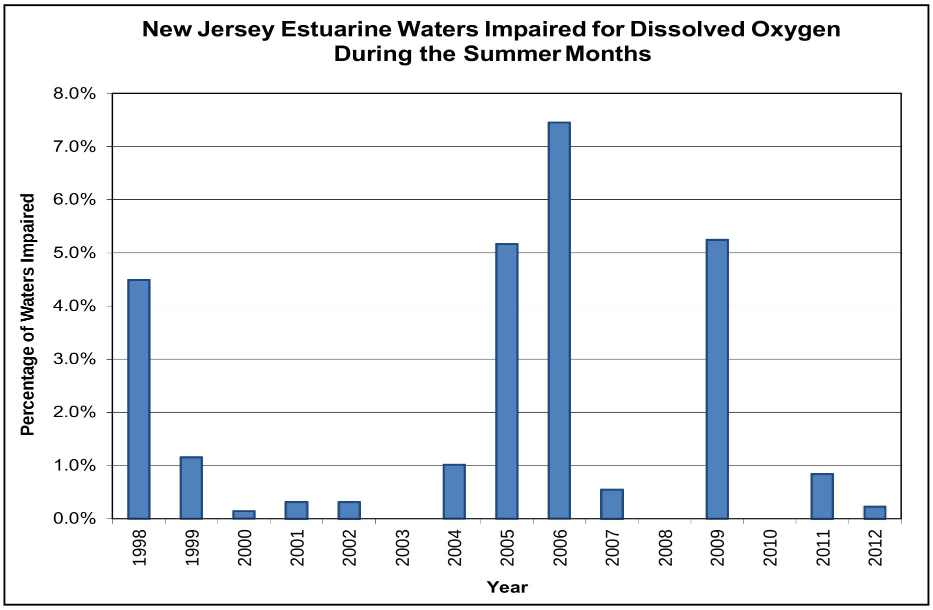

Figure 1: Percent of NJ Estuarine Waters Impaired for DO

Section 2: Dissolved Oxygen Data Collected

Because dissolved oxygen is essential to aquatic life, New Jersey has established criteria for oxygen levels in marine (5mg/L) and estuarine waters (4mg/L). Bottom samples are used for assessment in deeper water because they represent a "worst case" for dissolved oxygen concentrations, that can be exacerbated by poor mixing and limited light that would help support aquatic plants that assist in adding oxygen to the water.

Ocean Dissolved Oxygen Data

The two charts below show historical data (1979-2005) from the USEPA helicopter dissolved oxygen transect flights for areas 0 to 9 nautical miles off New Jersey's coast. The helicopter flights consisted of ten transects, each with 5 grab sample locations from 1 to 9 nautical miles offshore, extending from Sandy Hook to Cape May to provide a snapshot of coastal dissolved oxygen conditions. On average, 100 surface and 100 bottom samples were collected each summer season (June through August) until 1997. After 1997 only bottom samples were collected. Due to cost constraints, the helicopter transect flights were discontinued after 2005. The data show that each summer between 1979-2005, bottom-level dissolved oxygen concentrations fell below 5 mg/l, the State Surface Water Quality criteria for ocean waters with a minimum concentration of $\leq$2 mg/l in 16 of the 27 years (Figure 2 and 3). Surface samples showed very few instances when dissolved oxygen concentrations fell below 5 mg/l. For example, in 1990 a maximum of 2.8% of samples were less than 5 mg/l. Many years, however, there were no surface sample records below 5 mg/l. The difference observed between surface and bottom DO concentrations indicates strong vertical stratification.

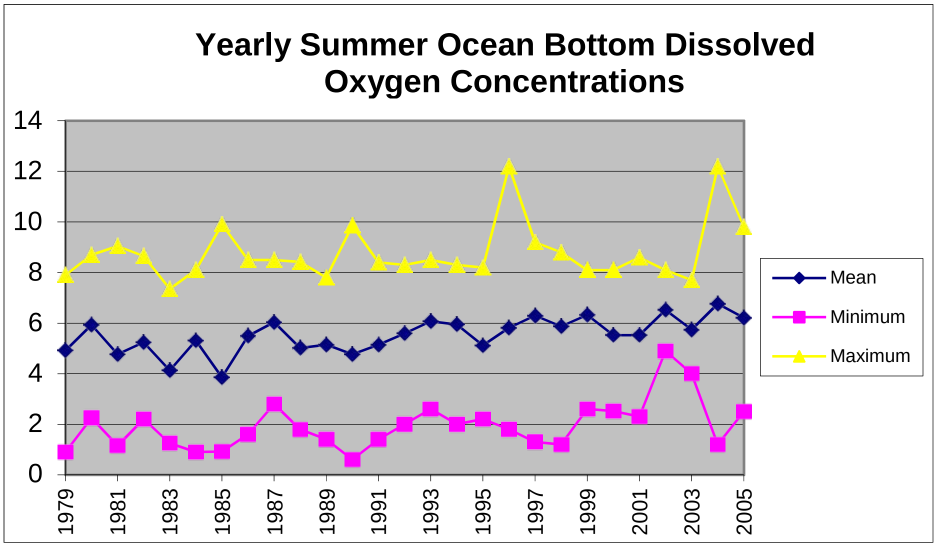

Figure 2: Yearly Summer Ocean Bottom Dissolved Oxygen Concentrations

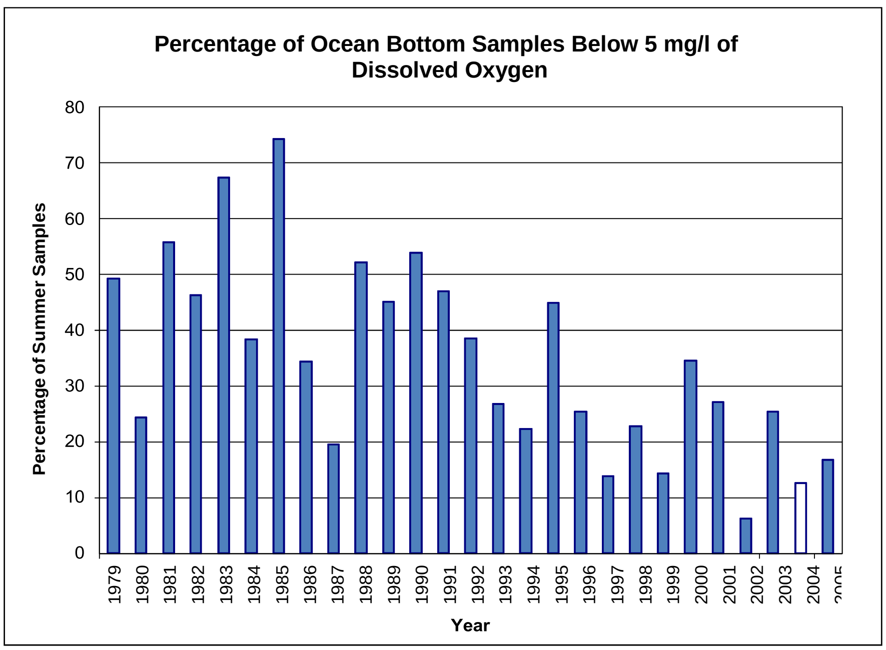

Figure 3: Percentage of Ocean Bottom Samples Below 5 mg/L of Dissolved Oxygen

Figures 2 and 3 show that ocean bottom low dissolved oxygen conditions occur on an annual basis, at least since 1979. However, data records are not available prior to 1979, thus no information on dissolved oxygen concentrations related to prior increasing in urbanization exists.

To further investigate impacts from ocean bottom low dissolved oxygen conditions and summer stratification, the NJDEP, USEPA, and Rutgers University have recently performed studies based on benthic macroinvertebrates off New Jersey coast. These studies were initiated in 2011 and are discussed in greater detail in Section 3 of this document.

Slocum Glider Ocean DO data

Routine Slocum glider work to measure dissolved oxygen in NJ coastal waters was initiated in 2011 to better understand the oxygen conditions and dynamics of near shore waters off the New Jersey Coast. The glider is deployed during the months of June-October. The deployments start in the north and will follow a sawtooth pattern moving east to west, top to bottom and from Sandy Hook in the north to Cape May in the south (Figure 4). The glider is fitted with sensors that record dissolved oxygen, temperature, salinity, and chlorophyll *a* at 1 second intervals during the deployment. An example of DO data from September 2012 deployment is provided in Figure 5.

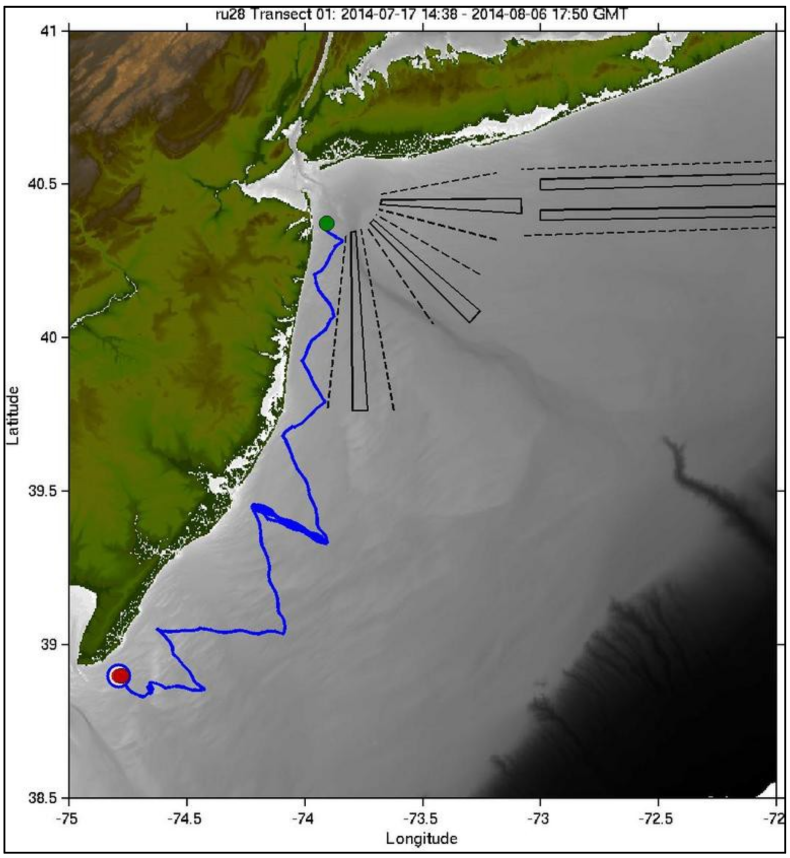

Figure 4: Example of glider path

Green and red dots represent start and end of deployment. Solid and dotted lines represent shipping lanes.

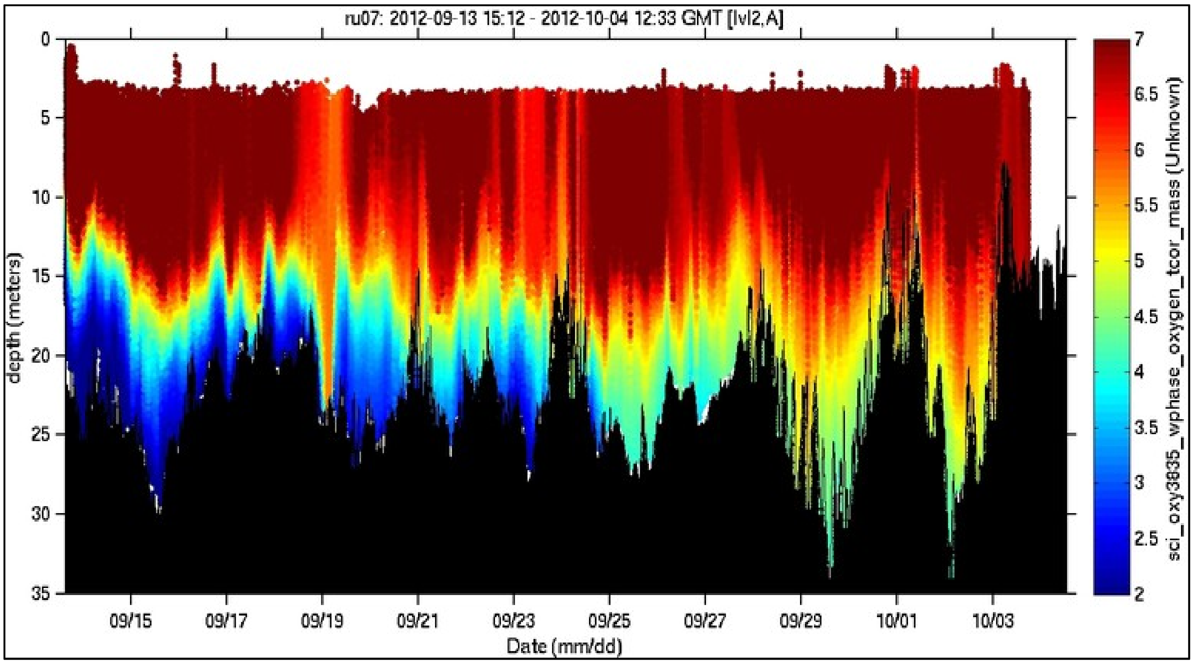

Figure 5: Dissolved Oxygen Data from September 2012 Slocum glider deployment

All of the glider quality assured data has been compiled into a database and grouped spatially into 32 grids (randomly and/or visually delineated based on prior knowledge of phytoplankton blooms occuring in some of the grids) (Figure 6) to preliminarily asses the large volume of information. These grids may be redesigned for future assessment. Below there is an example showing the differences observed between August and September of 2013, for Grid number 28, off Sandy Hook (Figure 7 and 10). These figures show a system where DO values changed drastically from August to September, with a larger portion of the water column containing DO readings lower than 5 mg/L for a longer period of time.

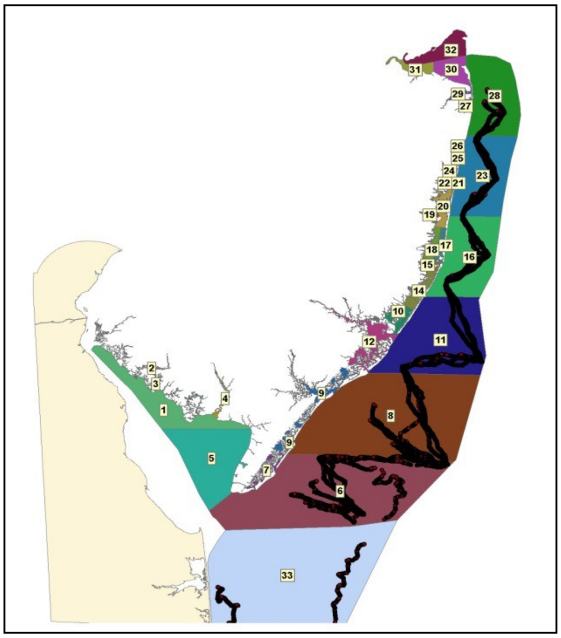

Figure 6: New Jersey Coast grids used in glider assessment

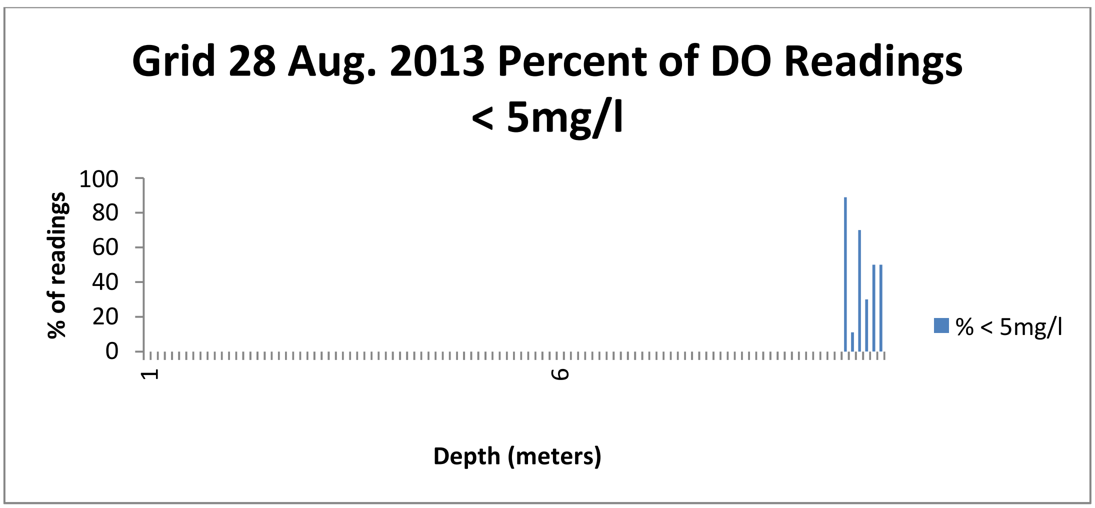

Figure 7: Percent of dissolved oxygen data <5 mg/L in Grid 28 in August 2013

(Percent based on 47,000 DO readings in 2 days (8/13-8/14). The percentage of results <5mg/L was limited to the deeper depths and did not reach 100% while most of the column DO is >5mg/L.)

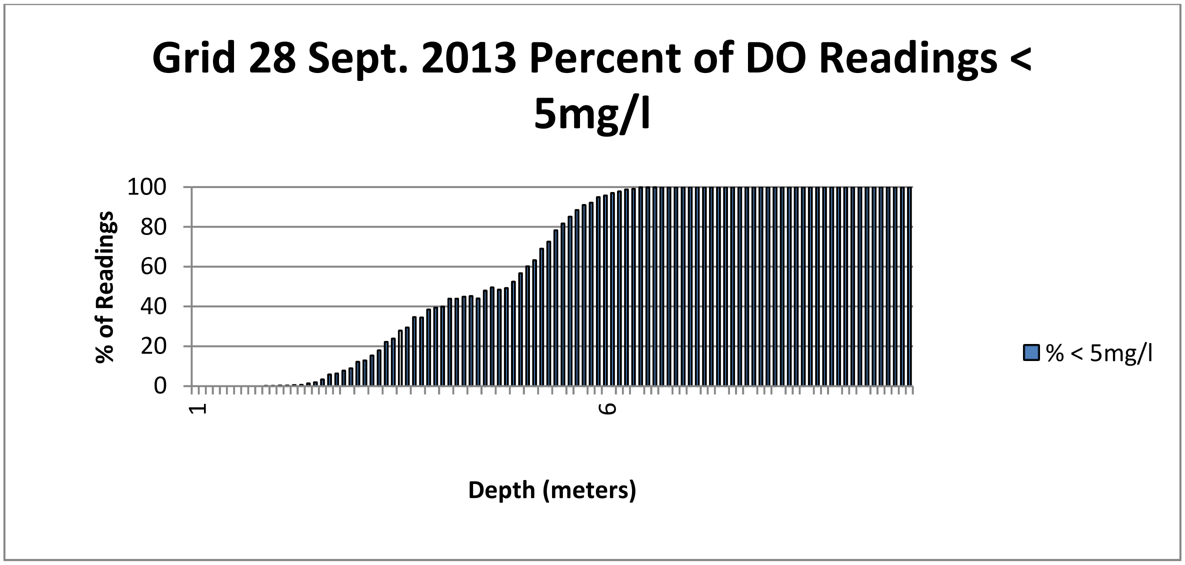

Figure 8: Percent of DO reading <5 mg/L for Grid 28 in September 2013
(Percentage based on 58,000 DO readings taken from 9/12-9/14/2013. The percentage of results <5 mg/L were more widespread throughout the water column with 100% <5 mg/L from 17 to 26 meters of depth.)

During August of 2013, the minimum dissolved oxygen concentration observed in grids 6, 8, 11, 16, 23 and 28 (Figure 9) declined with depth and showed an unusual increase near the bottom. The September 2013 data (Fig. 10) showed diversity in the rate of decline between grids and ultimately a lower dissolved oxygen concentration than August. The September data also shows an unusual oxygen increase near the bottom. Further assessment of the data from all years will be performed to verify if these bottom increases are a consistent pattern off the NJ coast or temporary anomalies.

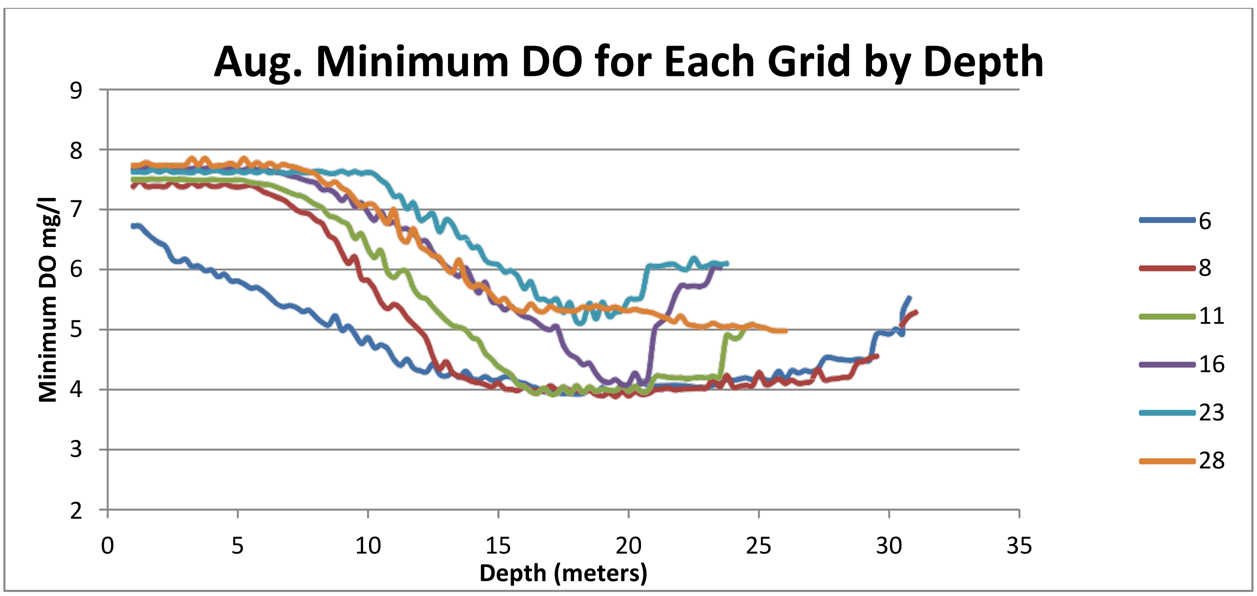

Figure 9: Minimum DO in six grids during August 2013

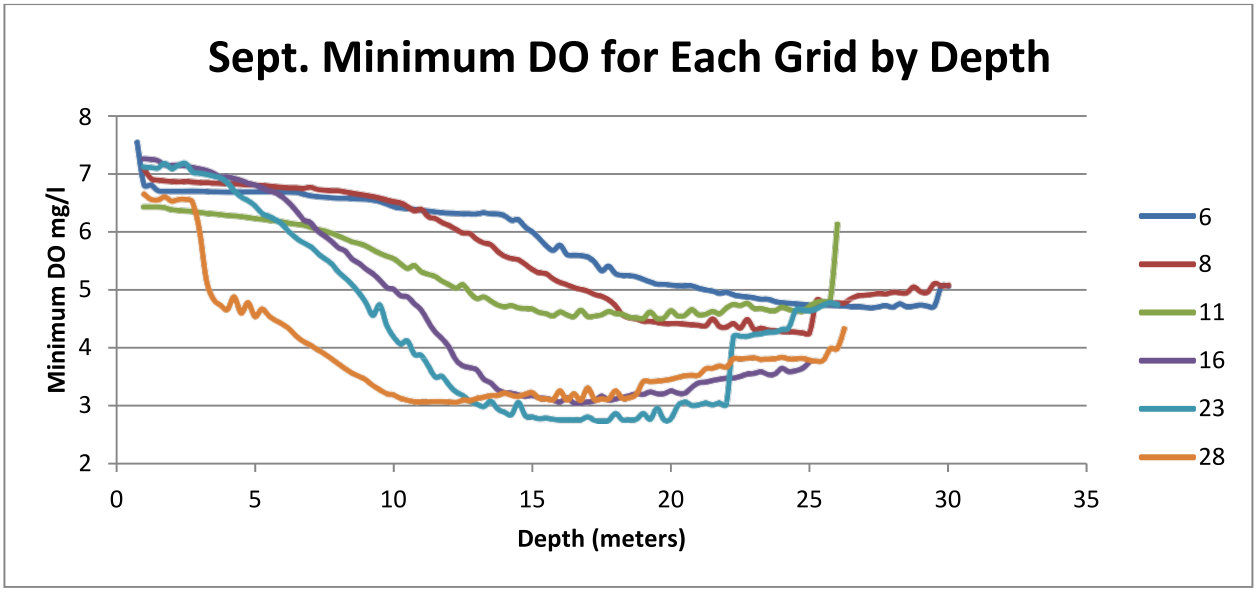

Figure 10: Minimum DO in six grids during September 2013

Currently, data analysis of the collected Slocum glider data is ongoing to discern annual and seasonal DO patterns of distribution.

Estuarine Dissolved Oxygen Data

Data collected in NJ estuaries is available for the time period between 1998 and 2012. These data show a high degree of variability from year to year. Figure 1 shows the trend for summer dissolved oxygen conditions over the 15-year period. The data assessed were from surface water grab samples, usually collected between 7 am and 11 am. Water samples collected during this time frame may not include the minimum dissolved oxygen concentration - which may occur during the very early morning hours, before sunrise. The percent of waters exhibiting impairment has varied over the years. These fluctuations can be caused by numerous factors such as the weather preceding the sample collection, water temperature, water quality parameters (e.g., nutrients, chlorophyll *a*), and the time of sample collection. The 2013-2015 estuarine DO data is currently being processed and results are not yet available.

Barnegat Bay Dissolved Oxygen Data

Between 1998 and 2012, Barnegat Bay exhibited very good dissolved oxygen conditions, with very few samples having results below the State's 4 mg/l surface water quality criteria for estuaries (Figure 11); eleven of the 15 years show no dissolved oxygen impairment within the Bay. DO was measured from surface and bottom grab water samples collected at a minimum of 15 fixed stations throughout the Bay each year at a minimum frequency of once every 3 months, between 7am and 11am, and therefore may not include the minimum dissolved oxygen concentration - which may occur during the very early morning hours, before sunrise, or between the quarterly sampling events.

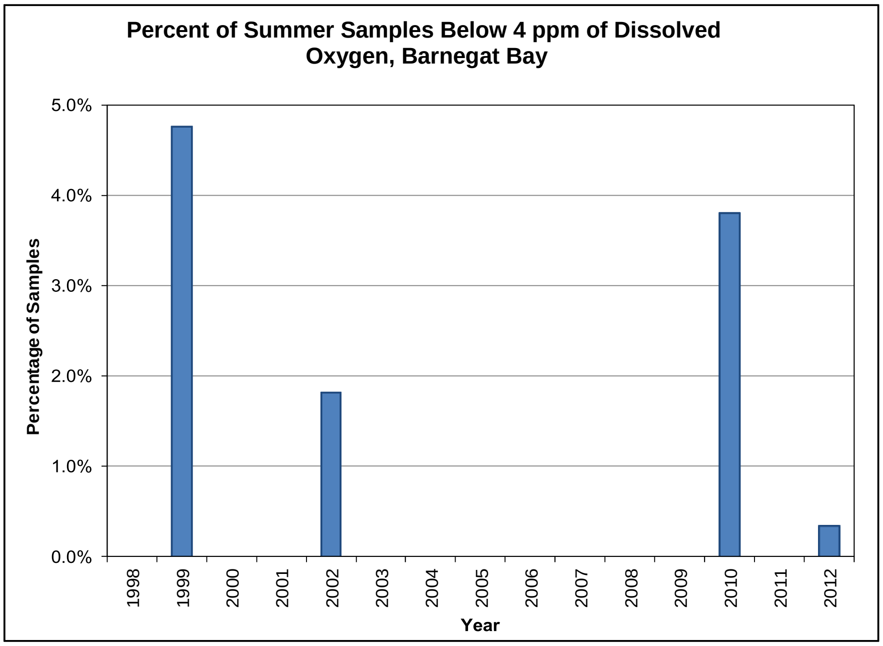

Figure 11: Percent of Summer Samples below 4 ppm of Dissolved Oxygen, Barnegat Bay

To supplement the fixed grab sample monitoring described above, four continuous monitoring buoys are located throughout the Barnegat Bay Estuary to measure the diurnal changes in the dissolved oxygen concentrations. The oxygen sensor in the buoy is located 3 feet below the surface which, in many areas of the bay, is about mid-depth in the water column. Barnegat Bay is a shallow and well mixed estuary, so mid-depth sampling should provide a good representation of the oxygen conditions. The continuous dissolved oxygen data collected from the buoys between May and November 2012 from Barnegat Bay show very few instances where dissolved oxygen dropped below 4 mg/l, except for the mouth of the Toms River.

Section 3: Benthic Index of Biological Integrity

In response to the listed impairment of the ocean waters due to bottom low DO and the persistent summer stratification of the surface and bottom water, NJDEP, initiated two studies to better understand the effects of low DO on biological communities off the NJ coast.

In the first study, Rutgers University's Institute of Marine and Coastal Sciences (IMCS) was contracted to design a study to characterize the ocean benthic community and to develop an Ocean Benthic Index to measure the biological health in near shore ocean waters. The 2011 report describes the development of a biotic index using macrofaunal benthic communities designed to assess the ecological condition of nearshore ocean waters along the New Jersey coast (Ramey, Kennish and Petrecca, 2011).

The second study, conducted by Rutgers University, was a comprehensive research initiative was initiated in 2011 to evaluate the condition of the Barnegat Bay based on benthic invertebrate fauna (Taghon, 2015 Report to NJDEP). The objective of this study was to develop quantitative measures to relate benthic community structure to variation in environmental characteristics in Barnegat Bay-Little Egg Harbor Estuary.

Ocean Benthic Index

Study design was based on 100 stations (random selection (background stations), plus wastewater treatment plant outfalls and areas known for hypoxic events) sampled in the 2007, 2009, and 2010 summer seasons for benthic macroinvertebrates, sediment characteristics and water quality parameters. Sites included wastewater treatment plant outfalls mixing zones (between 100 to 200 meters of the ocean discharge) and zones of initial dilution (from the pipe outlet out to 100 meters). A modified AZTI Multivariate Marine Biotic Index (AMBI (http://www.azti.es/) was deveoped based on weights of percentage of assigned macroinvertebrate tolerance groups. Details on project methods can be found in Ramey, Kennish and Petrecca (2011).

Water quality findings

Water quality parameters were measured in surface to bottom profiles, at 1 meter increments for pH, DO, salinity, and temperature.

Temperature: Temperature and stratification patterns varied greatly during the study period. In 2007 and 2009, the ocean waters displayed persistent stratification, while in 2010 they were very well mixed; 2007 and 2009 recorded ~2^{0}C and 5^{0}C difference in mean surface and bottom temperatures. In 2010, the difference between the average water temperatures from surface was less than 1 °C.

Dissolved oxygen: In 2010, all DO values were above 5 mg/l. The average minimum dissolved oxygen concentrations were essentially the same for the background samples and the mixing zone samples, 7.41 mg/l and 7.42 mg/l, respectively; the zone of initial dilution samples were slightly lower at 6.93 mg/l, but still displaying good oxygen conditions. From this data it can be concluded that the Ocean discharge outfalls, did not adversely impact the dissolved oxygen concentrations, at least during the 2010 study.

Salinity: Average surface salinities from the zone of initial dilution, mixing zone, and background stations displayed a range variation of maximum 0.5 PSU with a steady increase in the average surface salinities from the ZID to the background stations, likely due to the fresh water from the outfall riding to the surface above the denser seawater at the bottom. The bottom waters showed a smaller variation range, of 0.1 PSU.

Benthic Macroinvertebrate Community Findings

The initial application of the biotic index (Ramey, Kennish and Petrecca, 2011) indicated that 28% of stations sampled over both years were “unpolluted”, containing a relatively high proportion of species/taxa that are sensitive to organic enrichment representing a "normal or impoverished" community. The remaining 72% of stations also had a relatively high ecological status, classified as being “slightly polluted”. These communities contained a high proportion of species/taxa that are relatively tolerant of organic enrichment but are also known to occur under "normal" conditions.

In addition, it was found that patterns in species composition, distribution, and abundance were primarily influenced by natural sources of environmental variation (i.e., depth, sediment type, and "natural" levels of total organic carbon), rather than by pollution-related surrogates such as dissolved oxygen and "unnatural" levels of organic carbon consistent with organic enrichment.

Conclusions

The report concluded that dissolved oxygen criterion of 5 mg/L that was used in an assessment that reported 100% of New Jersey's ocean waters to be impaired due to hypoxia is well above the concentration expected to have a severe impact on benthic communities. It notes, however that although significant progress was made in developing a benthic index for the New Jersey coastal ocean with very positive findings related to its performance, results should be interpreted with caution until the index is further calibrated and properly validated.

Barnegat Bay Benthic Index

The Barnegat Bay-Little Egg Harbor (BB-LEH) Estuary is complex with respect to environmental variables known to affect benthic community composition. In July 2012, 2013, and 2014 one hundred stations were sampled throughout the bay. For this study, three sediment samples were taken at each sampling station. Two of the sediment samples were processed in their entirety for benthic invertebrate macrofauna while the third one was used for measurement of sediment properties. Surface and bottom water salinity, temperature, dissolved oxygen, and pH were also measured. A Multivariate Marine Biotic Index was developed to relate the proportion of benthic animals that belong to ecologically sensitive species to total nitrogen concentration and the dissolved oxygen saturation level in the water.

Water quality findings

Dissolved Oxygen: During the study period, bottom water DO varied across these sites between 2.1-10.4 mg/L (Table 2). There was no obvious spatial pattern in dissolved oxygen. Dissolved oxygen increased steadily from 2012 to 2013 to 2014.

Table 2: Summary data for dissolved oxygen measurements in Barnegat Bay

Dissolved Oxygen Concentration	Mean	Minimum	Median	Maximum
2012	5.8	4.0	5.9	7.4
2013	6.2	2.1	6.1	8.4
2014	6.7	4.6	6.5	10.4

Temperature: Over the 3-year project period, bottom water temperatures ranged from 21.5 to 28.8° with the coolest waters present in the central section of the bay near Barnegat Inlet and in the southern section near Little Egg Inlet. Warmest waters were in the northern half of the bay. The average bottom temperature was 25.6°C in 2013 and 2014, and 27°C in 2012.

Salinity: Bottom salinity ranged from 14.9 to 30.3 with lowest values recorded in the northern section of the bay, and highest in the central section of the bay and in Little Egg Harbor. There was little difference in salinity over the years 2012-2014. The distribution with latitude is typical for BB-LEH, with three salinity 'bands': highest salinity at latitudes ≤39.8, transitional salinity at 39.8 < latitude ≤39.925, and lowest salinities at latitude >39.925.

pH: The bottom water pH varied from 7.5 to 8.3 with highest values occurring in southern Little Egg Harbor, with no strong spatial pattern and little variation over the period 2012-2014.

Benthic Macroinvertebrate Community Findings

A total of 276 taxa were identified in this study. A subset of 220 of these taxa was used for further analyses and IBI development. The benthic community in BB-LEH was dominated by relatively few species with five taxa accounting for 50% of all individuals collected in 2014, and 48 taxa accounting for 90% of all individuals, many of them characteristic of un-impacted estuarine conditions.

The Multivariate Marine Biotic Index (M-AMBI) value was used to place a site into one of five categories: bad, poor, moderate, good, or high. In 2014, one station near the mouth of Toms River was classified as 'poor' and 10 stations, mostly in northern Barnegat bay, were classified as 'moderate'; eighty stations were classified as 'good' and six as 'high' (Figure). The average score was 'good' in all three years, although the average numerical value was lower in 2014.

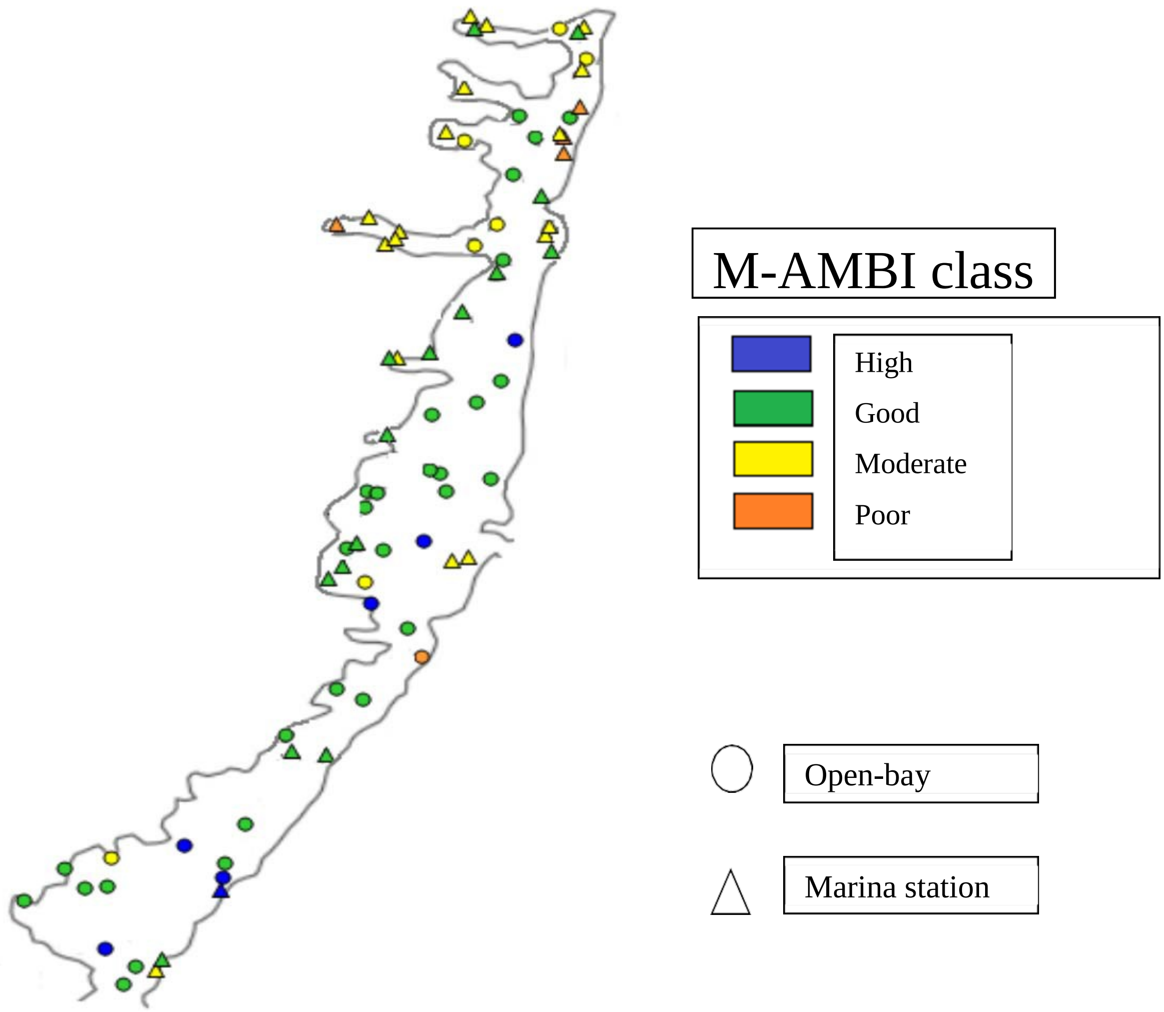

Figure 12: Classification of stations by M-AMBI in 2014 (from Taghon, 2014 Report to DEP)

Benthic Index Conclusions

Benthic macroinvertebrates were found abundant and diverse over the 3-year study period, with many taxa typical of reference, non-impacted estuarine habitats in the Virginian Biogeographic Province dominant, except for a few stations in the northern section of the bay, especially sites near major sources of freshwater input, such as the Toms River. Over 80% of sites were classified as in Good or High condition by the Multivariate AZTI Marine Biotic Index. The study concluded that overall the Barnegat Bay benthic invertebrate community was in good condition over the 3-year study period and a biological condition index was developed to relate the proportion of ecologically sensitive species to total nitrogen concentration and dissolved oxygen saturation level in the water.

References:

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New Jersey Administrative Code 7:9B (N.J.A.C. 7:9B), Surface Water Quality Standards (SWQS), Re-adopted November 16, 2009. Accessed online 2/2/2016 at: http://www.nj.gov/dep/rules/rules/njac7_9b.pdf

Ramey, P.A., Kennish, M.J., and Petrecca, R.M., Benthic Index Development: Assessment of Ecological Status of Benthic Communities in New Jersey Marine Coastal Waters, Report prepared for US Environmental Agency and New Jersey Department of Environmental Protection, December 2001 (accessed online 2/1/2016 at: *https://rucore.libraries.**rutgers**.edu/**rutgers**-lib/44203/PDF/1/*

Taghon, Gary, Grassle, J.P., Fuller, C.M., Petrecca, R.F., Ramey, P., Benthic Invertebrate Community Monitoring and Indicator Development for the Barnegat Bay-Little Egg Harbor Estuary, Report prepared for the New Jersey Department of Environmental Protection, available online at: http://nj.gov/dep/dsr/barnegat/final-reports/benthic-invertebrate-monitoring-year3.pdf Accessed online 6/21/2016)

APPENDIX B

Marine Fish of NJ

Marine Fish of New Jersey

There are approximately 450 species of vertebrate wildlife which can be found within the Garden State, along with 85 freshwater fish. Our bays, estuaries and marine waters can be home to 28 marine mammals and 336 marine finfish at some point during the year. This is an exceptional number of species for a state as small as New Jersey.

The majority of information in the table below was compiled through the work of Ken Able (citation below) and lists marine fish which can be found, along with their historical status as defined below:

Abbreviations:

A - Abundant
AS - Abundant in summer
ASF - Abundant in spring and falll
F - Frequent
R - Rare
T - Threatened

C - Common
C-A - Common-abundant
CS - Common in summer
CSF - Common in summer and fall
CW - Common in winter
CWS - Common in winter and spring

O - Occasional
OS - Occasional in summer
OSF - Occasional in summer and fall
OWS - Occasional in winter and spring

COMMON NAME	SCIENTIFIC NAME	STATUS
Myxinidae:		
Atlantic Hagfish	Myxine glutinosa	R
Petromyzontidae:		
Sea Lamprey	Petromyzon marinus	C
Odontaspididae:		
Sand Tiger	Odontaspis taurus	A
Alopiidae:		
Bigeye Thresher Shark	Alopias superciliosus	O
Thresher Shark	Alopias vulpinus	R
Cetorhinidae:		
Basking Shark	Cetorhinus maximus	R
Lamnidae:		
White Shark	Carcharadon carcharias	R
Shortfin Mako	Isurus oxyrinchus	R
Porbeagle	Lamna nasus	R

COMMON NAME	SCIENTIFIC NAME	STATUS
Scyliorhinidae:		
False Cat Shark	Pseudotriakis microdon	R
Chain Dogfish	Scyliorhinus retifer	A
Carcharhinidae:		
Silky Shark	Carcharhinus falciformis	R
Bull Shark	Carcharhinus leucas	R
Blacktip Shark	Carcharhinus limbatus	R
Dusky Shark	Carcharhinus obscurus	CS
Sandbar Shark	Carcharhinus plumbeus	AS
Tiger Shark	Galeocerdo cuvier	R
Smooth Dogfish	Mustelus canis	A
Lemon Shark	Negaprion brevirostris	R
Blue Shark	Prionace glauca	C
Atlantic Sharpnose Shark	Rhizoprionodon terraenovae	R
Sphyrnidae:		
Scalloped Hammerhead	Sphyrna lewini	R
Bonnethead	Sphyrna tiburo	R
Smooth Hammerhead	Sphyrna zygaena	R
Squalidae:		
Spiny Dogfish	Squalus acanthias	ASF
Squatinidae:		
Atlantic Angel Shark	Squatina dumeril	CSF
Pristidae:		
Smalltooth Sawfish	Pristis pectinata	R
Torpedinidae:		
Atlantic Torpedo	Torpedo nobiliana	R
Rajidae:		
Clearnose Skate	Raja eglanteria	A
Little Skate	Raja erinacea	A
Rosette Skate	Raja garmani	C
Barndoor Skate	Raja laevis	C
Winter Skate	Raja ocellata	A
Thorny Skate	Raja radiata	O

COMMON NAME	SCIENTIFIC NAME	STATUS
Dasyatidae:		
Southern Stingray	Dasyatis americana	R
Roughtail Stingray	Dasyatis centroura	C
Atlantic Stingray	Dasyatis sabina	R
Bluntnose Stingray	Dasyatis say	O
Spiny Butterfly Ray	Gymnura altavela	R
Smooth Butterfly Ray	Gymnura micrura	
Myliobatidae:		
Spotted Eagle Ray	Aetobatus narinari	R
Bullnose Ray	Myliobatis freminvillei	O
Cownose Ray	Rhinoptera bonasus	OS
Mobulidae:		
Manta	Manta birostris	R
Devil Ray	Mobula mobular	R
Acipenseridae:		
Shortnose Sturgeon	Acipenser brevirostrum	C in Delaware River
Atlantic Sturgeon	Acipenser oxyrhynchus	R
Elopidae:		
Ladyfish	Elops saurus	R
Tarpon	Megalops atlanticus	R
Albulidae:		
Bonefish	Albula vulpes	R
Anguilidae:		
American Eel	Anguila rostrata	A
Muraenidae:		
Green Moray	Gymnothorax funebris	R
Spotted Moray	Gymnothorax moringa	R
Ophichthidae:		
Speckled Worm Eel	Myrophis punctatus	R
Margined Snake Eel	Ophichthus cruentifer	O
Palespotted Eel	Ophichthus ocellatus	R
Congridae:		
Conger Eel	Conger oceanicus	C

COMMON NAME	SCIENTIFIC NAME	STATUS
Clupeidae:		
Blueback Herring	Alosa aestivalis	A
Hickory Shad	Alosa mediocris	C
Alewife	Alosa pseudoharengus	A
American Shad	Alosa sapidissima	T
Atlantic Menhaden	Brevoortia tyrannus	A
Atlantic Herring	Clupea harengus	CW
Gizzard Shad	Dorosoma cepedianum	O in saltwater
Round Herring	Etrumeus teres	O
Scaled Sardine	Harengula jaguana	R
Atlantic Thread Herring	Opisthonema oglinum	O
Spanish Sardine	Sardinella aurita	O
Engraulidae:		
Striped Anchovy	Anchoa hepsetus	C
Bay Anchovy	Anchoa mitchilli	A
Silver Anchovy	Engraulis eurystole	O
Ariidae:		
Gafftopsail Catfish	Bagre marinus	R
Osmeridae:		
Rainbow smelt	Osmerus mordax	T
Salmonidae:		
Rainbow Trout	Oncorhynchus mykiss	R
Atlantic Salmon	Salmo salar	R
Brown Trout	Salmo trutta	R
Gonostomatidae:		
Longtooth Anglemouth	Gonostoma elongatum	R
Mullers Pearlsides	Maurolicus muelleri	R
Oceanic Lightfish	Vinciguerria nimbaria	R
Chlorophthalmidae:		
Shortnose Greeneye	Chlorophthalmus agassizi	C at edge of continental shelf
Synodontidae:		
Inshore Lizardfish	Synodus foetens	O
Snakefish	Trachinocephalus myops	R

COMMON NAME	SCIENTIFIC NAME	STATUS
Paralepidae:		
White Barracudina	Notolepis rissoi	R
Duckbill Barracudina	Paralepis atlantica	R
Sharpchin Barracudina	Paralepis coregonoides	R
Myctophidae:		
Glacier Lanternfish	Benthosema glaciale	R
Smallfin Lanternfish	Benthosema suborbitale	R
Horned Lanternfish	Ceratoscopelus maderensis	C
Warming's Lanternfish	Ceratoscopelus warmingi	R
Longfin Lanternfish	Diogenichthys atlanticus	R
Benoit's Lanternfish	Hygophum benoiti	R
Slender Lanternfish	Hygophum reinhardti	R
Winged Lanternfish	Lampanyctus alatus	R
Largescale Lanternfish	Symbolophorus veranyi	R
Bregmacerotidae:		
Antenna Codlet	Bregmaceros atlanticus	R
Gadidae:		
Cusk	Brosme brosme	R
Fourbeard Rockling	Enchelyopus cimbrius	R?
Atlantic Cod	Gadus morhua	CWS
Haddock	Melanogrammus aeglefinus	OWS
Offshore Hake	Merluccius albidus	C
Silver Hake	Merluccius bilinearis	A
Atlantic Tomcod	Microgadus tomcod	C in Hudson and Hackensack Rivers
Pollock	Pollachius virens	Juveniles C
Red Hake	Urophycis chuss	A
Carolina Hake	Urophycis earlii	R
Spotted Hake	Urophycis regia	C
White Hake	Urophycis tenuis	O
Ophidiidae:		
Fawn Cusk-eel	Lepophidium profundorum	A
Striped Cusk-eel	Ophidion marginatum	C
Crested Cusk-eel	Ophidion welshi	R

COMMON NAME	SCIENTIFIC NAME	STATUS
Batrachoididae:		
Oyster Toadfish	Opsanus tau	A
Lophiidae:		
Goosefish	Lophius americanus	C
Antennariidae:		
Striated Frogfish	Antennarius striatus	R
Sargassumfish	Histrio histrio	R
Chaunacidae:		
Redeye Gaper	Chaunax stigmaeus	R
Exocoetidae:		
Clearwing Flyingfish	Cypselurus comatus	R
Bandwing Flyingfish	Cypselurus exciliens	R
Spotfin Flyingfish	Cypselurus furcatus	R
Atlantic Flyingfish	Cypselurus melanurus	R
Flying Halfbeak	Euleptorhampus velox	R
Ballyhoo	Hemiramphus brasiliensis	R
Silverstripe Halfbeak	Hyporhamphus unifasciatus	O
Belonidae:		
Flat Needlefish	Ablennes hians	R
Atlantic Needlefish	Strongylura marina	CS
Agujon	Tylosurus acus	R
Scomberesocidae:		
Atlantic Saury	Scomberesox saurus	R
Cyprinodontidae:		
Sheepshead minnow	Cyprinodon variegates	A
Marsh Killifish	Fundulus confluentus	
Banded Killifish	Fundulus diaphanous	A
Mummichog	Fundulus heteroclitus	A
Spotfin Killifish	Fundulus luciae	C
Striped Killifish	Fundulus majalis	A
Rainwater Killifish	Lucania parva	C
Poeciliidae:		
Eastern Mosquitofish	Gambusia holbrocki	C

COMMON NAME	SCIENTIFIC NAME	STATUS
Atherinidae:		
Rough Silverside	Membras martinica	C
Inland Silverside	Menidia beryllina	A
Atlantic Silverside	Menidia menidia	A
Holocentridae:		
Deep Water Squirrelfish	Holocentrus bullisi	R
Dusky Squirrelfish	Holocentrus vexillarius	R
Zeidae:		
Buckler Dory	Zenopsis cochifera	C
Gasterosteidae:		
Fourspine Stickleback	Apeltes quadracus	C
Threespine Stickleback	Gasterosteus aculeatus	C
Ninespine Stickleback	Pungitius pungitius	R
Fistularidae:		
Bluespotted Cornetfish	Fistularia tabacaria	R
Centriscidae:		
Longspine Snipefish	Macrorhamphosus scolopax	R
Syngnathidae:		
Lined Seahorse	Hippocampus erectus	CSF
Opposum Pipefish	Microphis brachyuros	R
Northern Pipefish	Syngnathus fuscus	A
Chain Pipefish	Syngnathus louisianae	R
Sargassum Pipefish	Syngnathus pelagicus	R
Dactyloperidae:		
Flying Gurnard	Dactylopterus volitans	R
Scorpaenidae:		
Blackbelly Rosefish	Helicolenus dactylopterus	A
Spinycheek Scorpionfish	Neomerinthe hemingwayi	R
Highfin Scorpionfish	Pontinus rathbuni	R
Barbfish	Scorpaena brasiliensis	R
Mushroom Scorpionfish	Scorpaena inermis	R
Smoothcheek Scorpionfish	Scorpaena isthmensis	R
Spotted Scorpionfish	Scorpaena plumieri	R

COMMON NAME	SCIENTIFIC NAME	STATUS
Acadian Redfish	Sebastes fasciatus	O
Triglidae:		
Armored Searobin	Peristedion miniatum	C at edge of continental shelf
Northern Searobin	Prionotus carolinus	A
Striped Searobin	Prionotus evolans	A
Cottidae:		
Sea Raven	Hemitripterus americanus	C
Grubby	Myoxocephalus aenaeus	C
Longhorn Sculpin	Myoxocephalus octodecemspinosus	C
Shorthorn Sculpin	Myoxocephalus scorpius	R
Agonidae:		
Alligatorfish	Aspidophoroides monopterygius	R
Cyclopteridae:		
Lumpfish	Cyclopterus lumpus	R
Atlantic Seasnail	Liparis atlanticus	R
Inquiline Seasnail	Liparis inquilinus	C
Percichthyidae:		
White Perch	Morone americana	A
Striped Bass	Morone saxatilus	A
Wreckfish	Polyprion americanus	R
Serranidae:		
	Anthias woodsi	O
Black Sea Bass	Centropristis striata	A
Red Grouper	Epinephelus morio	R
Warsaw Grouper	Epinephelus nigritus	R
Snowy Grouper	Epinephelus niveatus	R
Black Grouper	Mycteroperca bonaci	R
Gag	Mycteroperca microlepis	R
Priacanthidae:		
Glasseye snapper	Priacanthus cruentatus	R
Malacanthidae:		
Blackline Tilefish	Caulolatilus cyanops	R
Tilefish	Lopholatilus chamaeleonticeps	A

COMMON NAME	SCIENTIFIC NAME	STATUS
Pomatomidae:		
Bluefish	Pomatomus saltatrix	A
Rachycentridae:		
Cobia	Rachycentron canadum	R
Echeneidae:		
Sharksucker	Echeneis naucrates	R
Whitefin Sharksucker	Echeneis neucratoides	R
Marlinsucker	Remora osteochir	R
Remora	Remora remora	R
White Suckerfish	Remorina albescens	R
Carangidae:		
African Pompano	Alectis ciliaris	R
Yellow Jack	Caranx bartholomaei	R
Blue Runner	Caranx crysos	OSF
Crevalle Jack	Caranx hippos	CSF
Horse-eye Jack	Caranx latus	R
Bar Jack	Caranx ruber	O
Atlantic Bumper	Chloroscombrus chrysurus	R
Round Scad	Decapterus punctatus	R
Pilotfish	Naucrates ductor	R
Leatherjack	Oligoplites saurus	O
Bigeye Scad	Selar crumenophthalmus	R
Atlantic Moonfish	Selene setapinnis	OS
Lookdown	Selene vomer	OS
Greater Amberjack	Seriola dumerili	R
Almaco Jack	Seriola rivoliana	R
Banded Rudderfish	Seriola zonata	OS
Florida Pompano	Trachinotus carolinus	CS
Permit	Trachinotus falcatus	CS
Palometa	Trachinotus goodei	CS
Rough Scad	Trachurus lathami	R
Cottonmouth Jack	Uraspis secunda	R
Coryphaenidae:		

COMMON NAME	SCIENTIFIC NAME	STATUS
Dolphin	Coryphaena hippurus	CS
Bramidae:		
Atlantic pomfret	Brama brama	R
Lutjanidae:		
Schoolmaster	Lutjanus apodus	R
Red Snapper	Lutjanus camprechanus	R
Cubera Snapper	Lutjanus cyanopterus	R
Gray snapper	Lutjanus griseus	OS
Yellowtail snapper	Ocyurus chrysurus	R
Vermillion snapper	Rhomboplites aurorubens	R
Lobotidae:		
Tripletail	Lobotes surinamensis	
Gerreidae:		
Irish pompano	Diapterus auratus	R
Spotfin mojarra	Eucinostomus argenteus	R
Silver jenny	Eucinostomus gula	R
Tidewater mojarra	Eucinostomus harengulus	R
Flagfin mojarra	Eucinostomus melanopterus	R
Haemulidae:		
Pigfish	Orthopristis chrysoptera	R
Sparidae:		
Sheepshead	Archosargus probatocephalus	R
Sea bream	Archosargus rhomboidalis	R
Spottail pinfish	Diplodus holbrooki	R
Pinfish	Lagodon rhomboides	R
Scup	Stenotomus chrysops	A
Sciaendae:		
Silver perch	Bairdiella chrysoura	C
Spotted seatrout	Cynoscion nebulosus	R
Weakfish	Cynoscion regalis	A
Banded drum	Larimus fasciatus	R
Spot	Leiostomus xanthurus	C-A
Southern kingfish	Menticirrhus americanus	O

COMMON NAME	SCIENTIFIC NAME	STATUS
Northern kingfish	Menticirrhus saxatilis	C
Atlantic croaker	Micropogonias undulatus	C
Black drum	Pogonias cromis	C
Red drum	Sciaenops ocellatus	O in Delaware Bay
Mullidae:		
Red goatfish	Mullus auratus	R
Spotted goatfish	Pseudupeneus maculatus	R
Kyphosidae:		
Bermuda chub	Kyphosus sectatrix	R
Ephippidae:		
Atlantic spadefish	Chaetodipterus faber	R
Chaetodontidae:		
Foureye butterflyfish	Chaetodon capistratus	R
Spotfin butterflyfish	Chaetodon ocellatus	F in late summer
Banded butterflyfish	Chaetodon striatus	R
Pomacanthidae:		
Gray angelfish	Pomacanthus arcuatus	R
Pomacenthidae:		
Sergeant major	Abudefduf saxatilus	R
Mugilidae:		
Striped mullet	Mugil cephalus	A
White mullet	Mugil curema	A
Sphyraenidae:		
Great barracuda	Sphyraena barracuda	R
Northern sennet	Sphyraena borealis	C
Polynemidae:		
Atlantic threadfin	Polydactylus octonemus	R
Labridae:		
Tautog	Tautoga onilis	A
Cunner	Tautogolabrus adsperus	C
Scaridae:		
Emerald parrotfish	Nicholsina usta	R
Zoarcidae:		

COMMON NAME	SCIENTIFIC NAME	STATUS
Ocean pout	Macrozoarces americanus	C
Stichaeidae:		
Snakeblenny	Lumpenus lumpretaeformis	R
Arctic shanny	Stichaeus punctatus	R
Radiated shanny	Ulvaria subbifurcata	R
Pholidae:		
Rock gunnel	Pholis gunnelus	R
Anarhichadidae:		
Atlantic wolffish	Anarhichas lupus	R
Uranoscopidae:		
Northern stargazer	Astroscopus guttatus	O
Blenniidae:		
Striped Blenny	Chasmodes bosquianus	O
Crested Blenny	Hypleurochilus germinatus	R
Feather Blenny	Hypsoblennius hentz	O
Seaweed Blenny	Parablennius marmoreus	R
Ammodytidae:		
American Sand Lance	Ammodytes americanus	A
Northern Sand Lance	Ammodytes dubius	A
Eleotridae:		
Fat Sleeper	Dormitator maculatas	R
Gobiidae:		
Darter Goby	Gobionellus boleosoma	R
Highfin Goby	Gobionellus oceanicus	R
Naked Goby	Gobiosoma bosc	A
Seaboard Goby	Gobiosoma ginsburgi	O
Acanthuridae:		
Ocean Surgeon	Acanthurus bahianus	R
Blue Tang	Acanthurus coeruleus	R
Trichiuridae:		
Oilfish	Ruvettus pretiosus	R
Atlantic Cutlassfish	Trichiurus lepturus	R
Scombridae:		

COMMON NAME	SCIENTIFIC NAME	STATUS
Wahoo	Acanthocybium solandri	R
Frigate Mackerel	Auxis thazard	R
Little Tunny	Euthynnus alletteratus	CS
Skipjack Tuna	Katsuwonus pelamis	R
Atlantic Bonito	Sarda sarda	O
Chub Mackerel	Scomber japonicus	R
Atlantic Mackerel	Scomber scombrus	A
King Mackerel	Scomberomorus cavalla	O
Spanish Mackerel	Scomberomorus maculates	O
Cero	Scomberomorus regalis	O
Albacore	Thunnus alalunga	C
Yellowfin Tuna	Thunnus albacares	C
Bigeye Tuna	Thunnus obesus	O
Bluefin Tuna	Thunnus thynnus	CS
Xiphiidae:		
Swordfish	Xiphias gladias	CS
Istiophoridae:		
Sailfish	Istiophorus platypterus	R
Blue Marlin	Makaira nigricans	R
White Marlin	Tetrapterus albidus	C
Stromateidae:		
Black Ruff	Centrolophus niger	R
Black Fathead	Cubiceps baxteri	R
Barrelfish	Hyperoglyphe perciformis	R
Harvestfish	Peprilus alepidotus	O
Butterfish	Peprilus triacanthus	A
Freckled Driftfish	Psenes cyanophrys	R
Bluefin Driftfish	Psenes pellucidus	R
Bigeye Squaretail	Tetragonurus atlanticus	R
Bothidae:		
Twospot Flounder or Spottail Flounder	Bothus robinsi	R
Gulf Stream Flounder	Citharichthys arctifrons	A
Horned Whiff	Citharichthys cornutus	R

COMMON NAME	SCIENTIFIC NAME	STATUS
Angelfin Whiff	Citharichthys gymnorhinus	R
Bay Whiff	Citharichthys spilopterus	R
Smallmouth Flounder	Etropus microstomus	C
Gulf Flounder	Paralichthys albigutta	R
Summer Flounder	Paralichthys dentatus	A
Fourspot Flounder	Paralichthys oblongus	C
Windowpane	Scophthalmus aquosus	C
Dusky Flounder	Syacium papillosum	R
Pleuronectidae:		
Witch Flounder	Glyptocephalus cynoglossus	C
American Plaice	Hippoglossoides platessoides	R
Atlantic Halibut	Hippoglossus hippoglossus	R
Winter Flounder	Pleuronectes americanus	A
Yellowtail Flounder	Pleuronectes ferrugineus	C
Achiridae:		
Hogchoker	Trinectes maculatus	C
Cynoglossidae:		
Blackcheek Tonguefish	Symphurus plagiusa	R
Balistidae:		
Orange Filefish	Aluterus schoepfi	R
Gray Triggerfish	Balistes capriscus	R
Queen Triggerfish	Balistes vetula	R
Ocean Triggerfish	Canthidermis sufflamen	O
Fringed Filefish	Monacanthus ciliatus	R
Planehead Filefish	Monacanthus hispidus	R
Ostraciidae:		
Scrawled Cowfish	Lactophrys quadricornis	R
Trunkfish	Lactophrys trigonus	R
Smooth Trunkfish	Lactophrys triqueter	R
Tetraodontidae:		
Web Burrfish	Chilomycterus antillarum	R
Spotted Burrfish	Chilomycterus atinga	R
Striped Burrfish	Chilomycterus schoepfi	O

COMMON NAME	SCIENTIFIC NAME	STATUS
Porcupinefish	Diodon hystrix	R
Smooth Puffer	Lagocephalus laevigatus	OS
Northern Puffer	Sphoeroides maculatus	CS
Checkered Puffer	Sphoeroides testudineus	R
Molidae:		
Ocean Sunfish	Mola mola	O

Citation:

Able, K.W. 1992. Checklist of New Jersey saltwater fishes. Bull. N.J. Acad. Sci. 37(1):1-11

APPENDIX C

Literature Regarding Ecological Effects of Low Dissolved Oxygen Levels in Coastal Ecosystems

(prepared by Michael P. Weinstein, PhD, December 2014)

SOME *ECOLOGICAL* EFFECTS OF LOW DISSOLVED OXYGEN LEVELS IN COASTAL ECOSYSTEMS

Rabalais, N.N., Harper, D.E., Jr., Turner, R.E. 2001. Responses of nekton and demersal and benthic fauna to decreasing oxygen concentrations *In*: Rabalais, N.N and Turner, R.E. (Eds.) *Coastal and Estuarine Studies: Coastal Hypoxia, Consequences for Living Resources and Ecosystems*. American Geophysical Union, Washington, D.C.

- Fairly consistent pattern of progressive stress and mortality as the oxygen concentration decreases from 2 mg/l to anoxia (0 mg/l). Motile organisms (fish, portunid crabs, stomatopods, penaeid shrimp and squid) are seldom found in bottom waters with oxygen concentrations < 2 mg/l. Below 1.5 to 1 mg/l oxygen concentration, less motile and burrowing invertebrates exhibit stress behavior, such as emergence from the sediments, and eventually die if the oxygen remains low for an extended period. At minimal concentrations just above anoxia, sulfur oxidizing bacteria form white mats on the sediment surface, and at 0 mg/l, there is no sign of aerobic life, just black anoxic sediments.
- Effects leading to altered community structure and trophic interactions begin as dissolved oxygen concentrations approach 3 to 2 mg/l**.**
- The value of oxygen concentration for the different behavioral responses or when mortality occurs is not absolute, because (1) individual species vary in their physiological limits to oxygen deficiency, and (2) the history of severity or persistence of low oxygen for an organism is seldom known. Dashed lines (Figure 1) suggest approximate values for presence/absence or stress behavior, but solid lines indicate a rather precipitous decline in presence/absence and/or dead organisms.

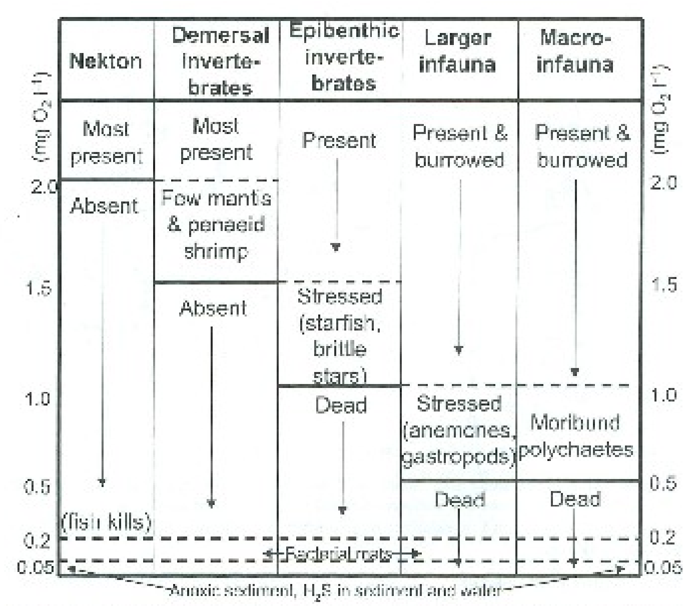

Figure 3. Progressive changes in fish and invertebrate fauna as oxygen concentratio decreases from 2 mg l^{-1} to anoxia (0 mg l^{-1}).

- Highly motile fishes (nekton) that are associated with the seabed (demersal) or more pelagic environs are seldom captured in a trawl taken when the oxygen level is below 2mg/l.
- While some demersal invertebrates were seen in ROV videotapes when oxygen levels were less than 2 mg/l, nekton and demersal fishes were not. On one occasion, fish were seen swimming in bottom waters of 0.95 mg/l (ROV observations). Eels, which occupy burrows in the seabed, were observed as low as 1 mg/l dissolved oxygen.
- Dead fish have not been seen on the bottom by divers, but a few dead fish were observed on the sediment surface when oxygen concentration was 0.4 mg/l during one 1993 ROV taping.
- The lack of fish is attributed, therefore, not to mortality, but to their avoidance of the hypoxic bottom layer by either (1) swimming upward to water above the oxycline, (2) horizontally in either an offshore/inshore direction or to the east or west of hypoxia or (3) a combination of both upward and horizontal movement. Large schools of sting rays (*Dasyatis americana*), a bottom resident and bottom feeder, were once observed swimming at the water's surface in a shoreward direction away from a large area of hypoxic bottom water. Other fish (benthic and benthopelagic species) that are normally bottom or near bottom dwellers were observed to be concentrated above the oxycline when the waters below are less than 2 mg/l.
- Extensive fish kills can occur when hypoxic water masses are pushed shoreward by offshore winds and upwelling events. In one such instance in 1990, more than 150,000 dead fish littered the beach off Grand Isle, LA. Shallow waters in the area were observed to have oxygen concentrations between 0.2 and 0.4 mg/l the day following the fish kill.
- The presence of hypoxic bottom waters over an area as large as 20,000 km2 results in the removal of a large portion of essential habitat for commercially important shrimps (Penaeidae) during part of the summer.
- In the hypoxic zone off Louisiana where soft sediments predominate, there are no attached epifaunal organisms such as sponges or soft coral. Similarly, biofouling communities of barnacles, hydroids, bryozoans, anemones and ascidians do not occur below a persistent oxycline where dissolve oxygen falls below 2 mg/l.
- Pihl et al. (1992) indicate that short-lived hypoxia did not appear to lessen habitat value for fisheries species and in fact may have facilitated predation on benthos at times when the infauna were stressed from low oxygen. In this scenario, enhancement of energy transfer may be temporarily facilitated by hypoxia.

Chesney, E.J., Baltz, D.M. 2001. The effects of hypoxia on the northern Gulf of Mexico coastal ecosystem: a fisheries perspective *In*: Rabalais, N.N and Turner, R.E. (Eds.) *Coastal and Estuarine Studies: Coastal Hypoxia, Consequences for Living Resources and Ecosystems*. American Geophysical Union, Washington, D.C.

- Goals of study – (1) review the complex of interacting factors that together with hypoxia in the northern Gulf of Mexico that influence fish habitat and fish production, and (2) specifically evaluate potential effects on the dominant nekton (fishes and mobile macroinvertebrates) in the system.
- Two questions were addressed – (1) what have been the effects of hypoxia on the long-term sustainability of fishery production in the region, and (2) have there been any effects on nekton community structure that are clearly attributable to hypoxia. The author caution that ecosystem complexity and interacting factors make the answer to these questions very challenging. For example, the process of harvesting abundant fishes as well as other environmental impacts affecting fishes and their habitats (wetland loss, HAB) are also likely to confound the analysis of hypoxia effects. Additionally, hypoxia does not affect all species or life stages of nekton equally.

- Two established linkages complicate the analysis of the effects of hypoxia on fisheries production – (1) fisheries production and nutrient enrichment are positively correlated in many marine ecosystems, and (2) and nutrient enrichment and hypoxia are also coupled and strongly correlated.
- Fisheries landings data from 1950 to 1997 in the region have increased steadily to more than 1.5 billion pounds (769,000 Mt) and have remained above that level since 1969. The dominant species contributing to the catch is the Gulf menhaden, a pelagic planktivore that might be expected to benefit from eutrophication (Govoni 1997). The overall trend in the hypoxic region of the Gulf, the "fertile crescent" is the same as for the remainder of the Gulf. Other commercial species such as red snapper, mackerel and cobia have maintained or increased their populations in the past decade (since about 1990). Recreational species like the red drum have maintained their populations too.
- The authors conclude that the current status of fisheries production remains strong in the "fertile crescent" (north-central Gulf of Mexico). Additionally, "it also seems likely that if fisheries production has been affected by the hypoxia, any effects on production are either secondary to the impacts from fishing activities, or that the effects of hypoxia are obscured by fishing effects and/or other impacts to nekton populations (wetland loss, directed fisheries, etc).
- Several different trawl (by-catch) studies support the hypothesis that significant structural changes in nekton communities have taken place over time with a general pattern of pelagic species becoming more abundant and some of the dominant demersal species declining in prominence. Most compelling evidence comes from a comparison of the composition of trawl bycatch in the shrimp fishery between the 1930s and 1989. Two planktivores, bay anchovy and Gulf menhaden moved from 3rd and 6th rank to 1 and 2, respectively. Other formerly low ranked planktivorous species also made substantial also made substantial upward climbs in the by-catch. Virtually all of the trawled ground-fishes were relatively less abundant while all the small pelagic fishes were relatively more abundant as by-catch. The authors conclude that there has "probably been" a significant change in nekton community structure in the past 60 years… the critical question is what caused these changes? Among the bottom dwelling species that declined, the star drum population was among the more significant decliners… species like this that are demersal, spawn offshore in summer and feed on small benthos are likely to be among those that are most likely affected by hypoxia.
- There is little doubt that some mortality of the early life stages of fish and other nekton due to low oxygen must occur on the Louisiana-Texas shelf. [But] there are likely to be some mitigating factors that buffer the effects of hypoxia on early life history stages; the principal mitigating factor for mortality during the early life-history of most nekton is that their mortality patterns can be highly compensatory [density dependent]. Compensatory reserve is greatest for short lived, highly fecund species (Cowan et al. 1999) … it is possible that mortality of early life stages is cause by hypoxia is not a major factor affecting recruitment of most nekton at this time.
- It is evident that somehow the substantial biomass and production of demersal fish and invertebrates (commercial shrimp and crabs) associated with the Gulf of Mexico hypoxic zone are being supported by the available benthic secondary production (Chesney et al. 2000). It is hypothesized that mid-shelf losses to benthic production associated with hypoxia during summer, may be compensated for by enhanced shelf wide benthic production on the Texas-Louisiana shelf throughout the rest of the year and by downstream effects of eutrophication … thus a dilemma posed by management calling for nutrient reduction strategies is that nutrient enrichment has had a significant positive effect on secondary production of coastal marine systems. We conclude that the exploited nekton populations in the Gulf of Mexico are able to tolerate the effects of hypoxia without obvious major consequences for their recruitment, production or population health.

2001. Caddy, J.F. A brief overview of catchment basin effects on marine fisheries *In*: Rabalais, N.N and Turner, R.E. (Eds.) *Coastal and Estuarine Studies: Coastal Hypoxia, Consequences for Living Resources and Ecosystems*. American Geophysical Union, Washington, D.C.

- It would be misleading to consider all levels of nutrient runoff as purely negative phenomena from the perspective of fisheries, even though this may be valid or some sectors. Increased management and research emphasis should probably be on looking at the marine catchment basin (MCB) phenomena as a whole and summing up the net gains and losses from nutrient runoff to the various economic sectors operating within the MCB.

Turner, R.E. 2001. Some effects of eutrophication on pelagic and demersal marine food webs *In*: Rabalais, N.N and Turner, R.E. (Eds.) *Coastal and Estuarine Studies: Coastal Hypoxia, Consequences for Living Resources and Ecosystems*. American Geophysical Union, Washington, D.C.

- Central question 1: how does water quality change associated with hypoxia affect carbon and energy flow through continental shelf food webs including those in the northern Gulf of Mexico?
- There is no question that the total biomass of fish and benthic macrofauna may be limited by the productivity of phytoplankton in surface waters for all, or part, of the some ecosystems.
- Food chain theory suggests that both trophic level number and biomass in the top level are proportional to food enrichment**.** In other words, food web structure may not be stable with eutrophication, intense fisheries harvest, anticipated climate changes, or introduction of new species.
- Modeling results highlighted the importance of the 10-15% of the carbon fixed in primary production lost into the water column as DOC was not appreciated as a microbial food source. The new paradigm suggested that bacterioplankton in the "Microbial Loop" played a significant role in this process by taking up DOC as an energy source.
- Central question 2: how much of the microbial food web is self-contained and how much is transferred into larger organisms?
- Results from several experiments suggest that eutrophication has the effect of driving coastal ecosystems towards a simpler, bloom like food web, where cell aggregation losses increase and the microbial loop is weakened.
- There are several broad generalizations that can be made from the construction of carbon budgets; 1) most carbon flow is not into pelagic fishes; the dominant flow of carbon in all seven ecosystems studied was into the detrital carbon pool. Carbon flow into the pelagic fish community averaged only 3% of the primary production, but was four times more than that by demersal fishes and invertebrates; 2) there is a rather inefficient transfer of energy between pelagic and demersal food webs; and 3) carbon flows from primary producers in the pelagic fish community are not proportional among the ecosystems studied.

TABLE 2. Some food web characteristics of carbon fluxes for seven continental shelf budgets (derived from data in Walsh [1988]).

Continental Shelf	# Pelagic Trophic Levels	Primary Production ($g C m^{-2} y^{-1}$)	Carbon into Detritus Pool[a] ($g C m^{-2} y^{-1}$)	Carbon into Pelagic Fish[b] Production ($g C m^{-2} y^{-1}$)	Carbon into Pelagic/ Demersal Fish Production[c]
Outer Southeastern Bering Sea	4	102	99 (97%)	5.4 (5.3%)	1.9
Middle Southeastern Bering Sea	3	166	138 (83%)	5.4 (3.2%)	0.2
Gulf of Anadyr, Bering Sea	3	285	198 (69%)	6.3 (2.2%)	2.5
Alaska Coastal	3	50	27.5 (55%)	0.8 (1.6%)	2.7
New York	4	300	240 (80%)	3.9 (1.3%)	1.9
Texas-Louisiana	3	100	86 (86%)	6.0 (6.0%)	18
Florida-Georgia	4	149	90 (60%)	1.6 (1.1%)	1.0
Average	3.4	165	126 (75%)	4.2 (3.0%)	4.0

[a]Includes carbon exported or buried

[b]Pelagic flows include phytophagous fish and their predators

[c]Demersal flows include commercially-important invertebrates (e.g., shrimp and crabs) and flows from the benthos to fish

- Texas-Louisiana Shelf (Table 2) – the total production of shrimp (Penaeidae) and Gulf menhaden was 98% of the total animal production on this shelf!
- These two taxonomic groups are both dependent on wetlands. Also, for shrimp there is a direct relationship between wetland area and shrimp yields for all Gulf of Mexico estuaries. For both taxa, annual variations in landings can be described very well with statistical models of fishing effort and indicators of climate variations when young are in the estuary and before harvest. These observations suggest that eutrophication will not result in an increased population size (or harvest) if the dominant form of animal production on the shelf **[compare to Chesney et al., above].**
- Walsh (1988) noted the doubling of nitrate in the Mississippi River in the last several decades, which along with P inputs, raised phytoplankton production on the northern Gulf of Mexico coast to 300 gC m^{-2} y-1. While menhaden harvest increase 25% during the observation period (1962-1975), Walsh believed it was due to the expansion of the fishery rather than any increase in eutrophication related factors. He “inferred” that adult menhaden populations were not food limited, and commented that any increase in primary production associated with eutrophication was exported and did not flow through the fisheries stocks **[again, compare to Chesney et al., above]**.
- Thus it appears that export and burial, rather than in situ respiration, would likely become the ultimate fate for any surplus organic matter that is produced, leading perhaps to an expanded hypoxic zone. The inference of wetland dependent harvest yields and the results of two different modeling exercises suggest the same thing – increased phytoplankton production on the Texas-Louisiana shelf will result in more carbon export off this shelf and that further eutrophication of this shelf will result in no significant increase in shrimp and menhaden harvests, which collectively represent 98% of animal production **[again, compare to Chesney et al., above]**.

Brietburg, D.L., Pihl, L., and Kolesar, S.E. 2001. Effects of low dissolved oxygen on the behavior, ecology and harvest of fishes: a comparison of the Chesapeake Bay and Baltic-Kattegat systems *In*: Rabalais, N.N and Turner, R.E. (Eds.) *Coastal and Estuarine Studies: Coastal Hypoxia, Consequences for Living Resources and Ecosystems*. American Geophysical Union, Washington, D.C.

- Goals of the review: Examine the behavioral, ecological, and fisheries consequences of low dissolved oxygen concentations of fish assemblages.
- Tolerances and the capabilities for behavioral response change with ontogeny.
- For nearly all species tested, only about 1.0 mg/l separated the most and least sensitive species.
- Low DO has the potential to alter virtually all aspects of predator-prey relationships. It affects encounter rates, attack rates, and behaviors of prey that influence their susceptibility to predation. Lower growth rates of prey may alter size-dependent mortality (0bviosly if there is a greater effect on prey than predators. Finally, by altering the relative success or importance of various taxa of predators in the system, low DO has the potential to cause changes in the importance of alternate trophic pathways.

- Reduction in growth and feeding occurs at O_2 concentrations higher that those leading to rapid mortality. Changes in size distributions of predators and prey can influence outcome of size-based trophic interactions.
- Reduced growth rates occur at 4.3 mg l^{-1} for embryo through larval Atlantic silversides; 3.5 mg l^{-1} for newly metamorphosed summer flounder (Poucher and Coiro 1997). Growth of juvenile striped bass is more sensitive to low DO at high temperatures typical of surface waters during summer than in cooler water.
- Growth of plaice and dab is reduced at 4.1 to 2.5 mg l^{-1} (50 to 30 % O2 saturation) at 15 C and 31-35 psu.
- Combination of algal exudates and low DO reduces hatching success.
- Low oxygen levels may mobilize metals from sediments, e.g., Mn that at high concentrations acts as a nerve toxin, reducing neuromuscular performance (Baden and Neil 1998).

Synthesis section of paper:

- There are common features of the consequences and responses to low dissolved oxygen in estuaries and coastal waters that should have general applications ... there are a wide variety of effects – life history characteristics, physiological tolerances, and behavioral responses of fish, their predators and their prey – that lead to a wide variety of effects of low DO in the bottom layer of stratified coastal systems (summary figure below).

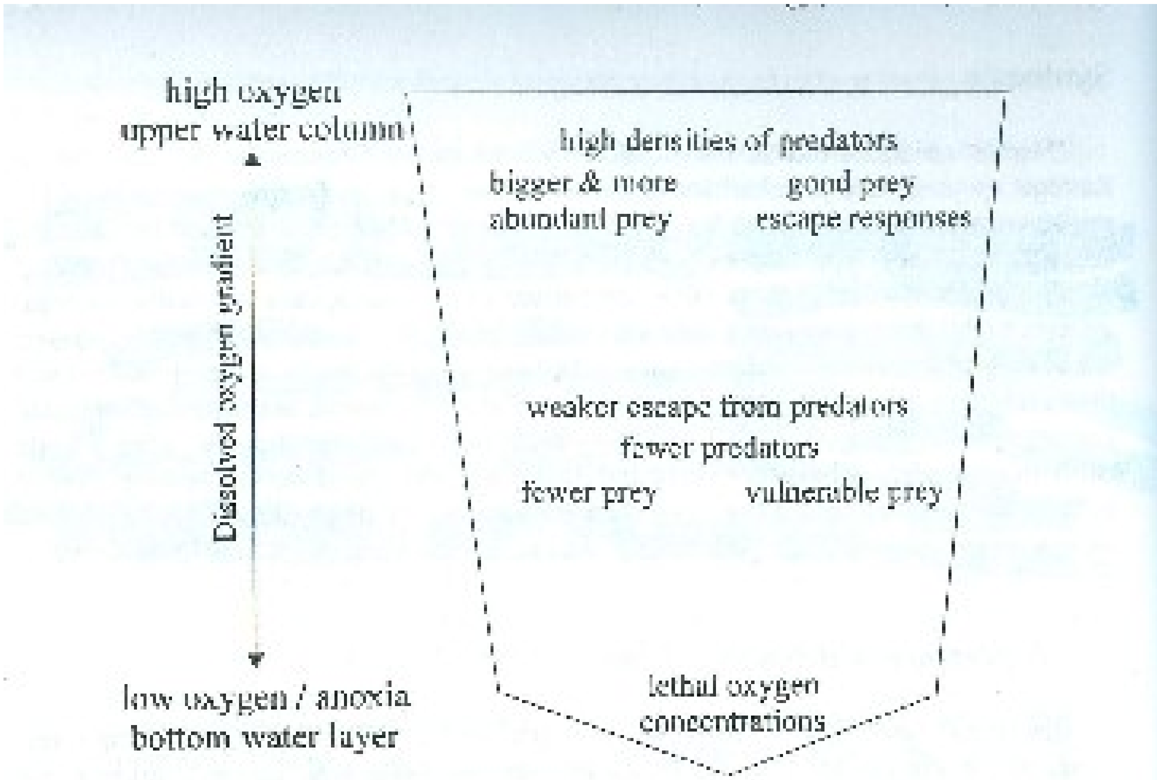

Figure 4. Risks and responses of fish to low dissolved oxygen in a water column with a vertical gradient or stratification. The ultimate effect of low dissolved oxygen in such systems will depend on the presence and form of physiological and behavioral responses by fish, their predators and their prey. A wide variety of consequences of low dissolved oxygen can occur within a single body of water because the vertical gradient or stratification of dissolved oxygen concentrations creates biologically significant physical structure within the water column. In addition, hypoxia, where not too severe, can have both positive and negative effects. For example, water depths with reduced but not severely stressful dissolved oxygen concentrations may have fewer predators of small fish as well as fewer prey on which fish can feed.

- Clearly, the early life stages of fishes are the most vulnerable, both because they are often more sensitive to low oxygen than juveniles and adults, and also because their behavioral responses are more limited.
- There is a positive relationship between fisheries landings (including shellfish) and nitrogen loadings in marine systems (Nixon 1992). In addition, individual growth rates of some species may respond positively to anthropogenic nitrogen loading (Boddeke and Hagel 1991).
- Total fish catches in the Baltic, dominated by herring, sprat and cod increased ten-fold from the 1920s to the 1980’s. In addition to increase fishing pressure, eutrophication as well as decreased predation by seals were also thought to be important factors (Hanson and Rudstrom 1990). Increased biomass and productivity above the halocline has resulted in a net doubling of benthic production in the Baltic. At present, the Baltic fishery requires about 10% of the primary production, compared to 1% at the turn of the [twenty first] century (Elmgren 1989).

- For herring and sprat, the effects of continued eutrophication can be positive, however, cod reproductive success is threatened by hypoxia and the stock will likely be negatively affected.
- Ultimately, at some level of nutrient loading, hypoxia, the negative effect of eutrophication most directly deleterious to high trophic levels, exceeds the positive effects of increased production.
- In response to a decline in striped bass populations, Coutant (1985) postulated the "temperature squeeze" hypothesis, suggesting that little suitable habitat remained in Chesapeake Bay for striped bass growth and well-being as a function of higher temperatures in surface water combined with lower oxygen levels in cooler bottom waters.
- The effects of hypoxia in different ecosystems will, of course, partly be a function types of species present, and geochemical/geophysical characteristics of the system.

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