Applying the System Wide Eutrophication Model (SWEM) for a Preliminary Quantitative Evaluation of Biomass Harvesting as a Nutrient Control Strategy for Long Island Sound

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ABSTRACT

Shellfish aquaculture and seaweed farming were quantitatively considered as additional means for removing nitrogen from Long Island Sound and fully attaining CT and NY water quality standards for dissolved oxygen. A mechanistic numerical model of Long Island Sound eutrophication processes, the System Wide Eutrophication Model (SWEM), was modified to empirically include the filtration of particulate organic nutrients by bivalves and the uptake of dissolved inorganic nutrients by seaweed. SWEM results suggest that minimum dissolved oxygen can be improved throughout the majority of Long Island Sound by as much as 2 mg/L. Coincident total nitrogen concentrations can be reduced by 0.15 mg/L. Calculated dissolved oxygen minima resulting from shellfish and seaweed aquaculture simulations are largely greater than 3.5 mg/L throughout the Sound. 3.5 mg/L of dissolved oxygen would be fully protective of the survival of the juveniles and adults of sensitive marine species (e.g., mud crab). Model results for two site specific metrics of living marine resource impairments, survival volume days and biomass volume days, are more favorable for shellfish aquaculture and seaweed farming cases than for high level reductions to nitrogen from atmospheric deposition and terrestrial point and non-point sources. In terms of attaining dissolved oxygen standards, the New York chronic standard would be met throughout Long Island Sound Response Regions 3 through 10 and large portions of Response Regions 1 and 2 with shellfish aquaculture and seaweed farming applied under current TMDL loading conditions.

1.0 INTRODUCTION

Hypoxia abatement is the primary focus of a currently in progress nitrogen Total Maximum Daily Load (TMDL) reassessment for Long Island Sound. The nutrient removal potential of aquaculture is of interest for the TMDL reassessment. Seaweed farms and aquaculture of shellfish present opportunities to potentially manage nutrients and alleviate hypoxia in eutrophicated waters such as Long Island Sound. It is therefore appropriate to consider applying these methods for Long Island Sound. For example, quantitative demonstrations of the benefits of seaweed and shellfish through numerical modeling have been undertaken by other researchers in Chesapeake Bay (Cerco and Noel 2007) and in Sungo Bay in the People's Republic of China (Duarte et al. 2003).

Shellfish function to reduce nutrients and abate hypoxia in two ways. First, the shellfish assimilate a large percentage of what they consume. Thus, shellfish present in Long Island Sound and then removed from the Sound could serve the purpose of extracting organic particle bound nutrients based on what they assimilate. Second, because of filter-feeding from the water column, shellfish play a role in focusing where and when organic particle bound nutrients from the water column not assimilated reach the sediment bed.

Seaweed uptake and assimilate dissolved inorganic nutrients, making them unavailable for phytoplankton growth. The uptake of inorganic nutrients by seaweed rather than phytoplankton inLong Island Sound would have the potential to abate hypoxia in the Sound if the seaweed and the incorporated nutrients were removed prior to senescence and die-off. The functioning of shellfish and seaweed are complementary rather than competitive since each uptake different nutrient phases, particulate organic and dissolved inorganic.

Preliminarily, a quantitative demonstration of the potential dissolved oxygen benefits of seaweed farms and aquaculture of shellfish has been completed for Long Island Sound. The quantitative demonstration of potential dissolved oxygen benefits for Long Island Sound using the System Wide Eutrophication Model (SWEM) is described below. SWEM results are one element of a planned future workshop further exploring seaweed farms and shellfish aquaculture as sustainable nutrient reduction alternatives for Long Island Sound hypoxia abatement.

2.0 METHODOLGY

2.1 Study Area

Long Island Sound is a coastal estuary connected to the Atlantic Ocean on its eastern end. On the western end of the Sound, two tidal straits, the East River and the Harlem River, connect Long Island Sound with the NY/NJ Harbor Estuary. The Long Island Sound Office has divided the water of Long Island Sound into ten Response Regions for evaluation purposes. Response Region 1 is located outside of, but adjacent to, Long Island Sound and includes the Harlem and East Rivers. Response Regions 2 through 10 are included in Long Island Sound. Figure 1 shows a map of the Long Island Sound Response Regions.

2.2 SWEM Structure

A previously developed numerical mass balance model of Long Island Sound, the System Wide Eutrophication Model (SWEM), mechanistically considers many aspects of water circulation, phytoplankton dynamics, nutrient cycling, and oxygen demand in Long Island Sound (Landeck Miller and St. John, 2006). SWEM is both three-dimensional and time-variable.

The hydrodynamic transport model used in SWEM (HydroQual 2007 a, 2001a, 2001d, 2001e, 2001f, Blumberg et al., 1999) is based on the Estuarine, Coastal and Ocean Model (ECOM) (Blumberg and Mellor, 1987) source code. The model is driven by water level, meteorological forcing, spatially and temporally varying surface heat flux, and freshwater fluxes from the numerous rivers, wastewater treatment plants, combined sewer overflows and runoff from the land that enter the waters of Long Island Sound, New York/New Jersey Harbor, and the New York Bight. The model solves a coupled system of differential, prognostic equations describing conservation of mass, momentum, heat and salt. A turbulence closure scheme is used to calculate vertical mixing. Model equations are transformed to an orthogonal curvilinear coordinate system in the horizontal and are further transformed to a bottom and free-surface following sigma coordinate system in the vertical. The model distinguishes between barotropic and baroclinic waves, solving the wave equations with different time steps. ECOM provides advection and dispersion terms and water temperatures needed for the SWEM eutrophication model.

The eutrophication model used in SWEM (Landeck Miller and St. John, 2006) is Row Column Aesop (RCA), a generalized, three-dimensional, time-varying water quality modeling program which has been described elsewhere (HydroQual 2007b, HydroQual, 2001a; HydroQual 2001c). The

RCA kinetics account for available light, phytoplankton growth, nutrient and organic carbon cycling, sediment dynamics, the dissolved oxygen balance, and phytoplankton primary production.

The light that algae can use for growth is modeled in SWEM as a function of four dependencies: incident solar radiation, the photoperiod or fraction of daylight, the depth of the water column, and light extinction or attenuation. The modeling framework used is an extension of the light curve analysis formulated by Steele (1962). The available light is important to primary production in Long Island Sound, the NY/NJ Harbor, and the NY Bight.

Phytoplankton growth is modeled in SWEM for two functional groups or assemblages: winter diatoms and summer flagellates. The reason phytoplankton are considered as two assemblages rather than as individual species is the growth rate of an individual population of phytoplankton in a natural environment is a complicated function of the species present and their differing reactions to solar radiation, temperature, and the balance between nutrient requirements and nutrient availability. The complex and often conflicting data pertinent to this problem have been reviewed exhaustively (Rhee 1973; Hutchinson 1967; Strickland 1965; Lund 1965; Raymont 1963). The available information is not sufficiently detailed to specify the growth kinetics for individual algal species in a natural environment, but we can divide the assemblages into distinct functional groups, namely diatoms and flagellates.

Nutrient and organic carbon cycling is modeled in SWEM as five phosphorus, six nitrogen, two silica and six organic carbon principal forms. Inorganic phosphorus is utilized by phytoplankton for growth and is returned to various organic and inorganic forms via respiration and predation. A fraction of the phosphorus released during phytoplankton respiration and predation is in the inorganic form and is readily available for uptake by other viable phytoplankton. The remaining fraction released is in the dissolved and particulate organic forms. The organic phosphorus must undergo mineralization, or bacterial decomposition, into inorganic phosphorous before it can be used by other viable phytoplankton

In SWEM, during algal respiration and death, a fraction of the algal cellular nitrogen is returned to the inorganic pool in the form of ammonia. The remaining fraction is recycled to the dissolved and particulate organic nitrogen pools. Organic nitrogen undergoes a bacterial decomposition, the end product of which is ammonia. Ammonia nitrogen, in the presence of nitrifying bacteria and oxygen, is converted to nitrite nitrogen and subsequently nitrate nitrogen (nitrification). Both ammonia and nitrate are available for uptake and use in cell growth by phytoplankton; however, for physiological reasons, the preferred form is ammonia.

Two silica forms are considered in SWEM. Available silica is dissolved and is utilized by diatoms during growth for their cell structure. Unavailable or particulate biogenic silica is produced from diatom respiration and diatom grazing by zooplankton. Particulate biogenic silica undergoes mineralization to available silica or settles to the sediment from the water column.

Pools of dissolved and particulate organic carbon are established in SWEM on the basis of timescale for oxidation or decomposition. Zooplankton consume algae and take up and redistribute algal carbon to the organic carbon pools via grazing, assimilation, respiration, and excretion. Since zooplankton are not directly included in the SWEM kinetics, the redistribution of algal carbon to the organic carbon pools by zooplankton is simulated by empirical distribution coefficients. An additional term, representing the excretion of dissolved organic carbon by phytoplankton during photosynthesis, is included in SWEM. This algal exudate is very reactive. The decomposition of organic carbon is assumed to be temperature and bacterial biomass-mediated. Since bacterial biomass is not directly included within SWEM, phytoplankton biomass is used as a surrogate variable. An additional loss mechanism of particulate organic matter is that due to filtration by benthic bivalves. This loss is handled in the SWEM kinetics by increasing the deposition of non-algal particulate organic carbon from the water column to the sediment.

In SWEM, sediment dynamics are modeled by a sediment sub-model. The mass balance equations of the sediment sub-model account for changes in particulate organic matter (carbon, nitrogen, phosphorus, and silica) in the sediments due to deposition from the overlying water column, sedimentation, and decay or diagenesis. The decay of particulate organic matter follows first-order kinetics as described by Berner (1964, 1974, and 1980). The end products of diagenesis or decay of the particulate organic matter include ammonia nitrogen, dissolved inorganic phosphorus and dissolved inorganic silica. These end products can undergo additional biological, chemical, and physical processing within the sediment layer such as nitrification, sorption, and exchange with the overlying water column. Of particular importance to the overlying water column is the calculation of sediment oxygen demand, SOD. A more complete development of the sediment sub-model theory is presented elsewhere (DiToro and Fitzpatrick 1993).

The SWEM dissolved oxygen balance includes both sources and sinks. Algal growth has two sources: the production of dissolved oxygen from photosynthetic carbon fixation and an additional source of oxygen from algal growth when nitrate rather than ammonia is utilized. Atmospheric reaeration is another source of dissolved oxygen. Sinks include algal respiration, nitrification, oxidation of carbonaceous material, and denitrification.

Primary production, an indirect measure of the depth integrated algal growth rate, is calculated by SWEM. Source and sink terms from the dissolved oxygen balance, photosynthetic carbon fixation and algal respiration, are both used to calculate primary production in oxygen units.

2.2.1 Previous SWEM Shellfish Modeling

SWEM as developed for eutrophication modeling applications includes an empirical relationship between bivalve carbon biomass (g C/m^2) and bivalve water column clearance rate (m/d). The relationship is based on *Rangia* from Chesapeake Bay following the approach of Powell et al. 1992. The clearance rates from the *Rangia* empirical relationship are used in SWEM to move organic particles from the water column to the sediment bed, mimicking the filtering effect of bivalves. Temperature dependencies are imposed on the relationship. With this relationship, because of the detailed hydrodynamic transport calculations included in SWEM, the food supply for the bivalves in the water filtered by the bivalves already includes the effects of physical processes such as current speed and vertical mixing. In other words, the SWEM hydrodynamic transport and particle settling calculations mechanistically control the time varying concentrations of phytoplankton and other particulate matter in the water overlying the bivalves and available for bivalve filter feeding. This is an advantage of SWEM as compared to bivalve growth models such as MUSMOD (Newell et al., 1998) which require making approximations of the food supply to bivalves over time.

In SWEM, depending upon the carbon biomass of the bivalves present, water column clearance rate ranges from 0.01 and 10 m/d, corresponding to filtration rates of roughly the same magnitude and range in units of m^3/g C/d.

Very limited filter-feeding bivalve abundance data, both biomass and spatial distribution, were available for estimating shellfish carbon biomass in the Long Island Sound portions of SWEM during SWEM development and calibration. The SWEM calibration includes 2.8 gm dry weight per square meter of filter-feeding bivalve biomass throughout Long Island Sound based on data. Sound-wide this amounts to approximately 63 million lbs of shellfish on a wet weight basis. Recent estimates of current shellfish abundance in Long Island Sound were obtained by the Long Island Sound Study Program Office from NY and CT for further verification.

CT reported 132,933 bags of oysters and 489,648 bags of hard clams harvested from the Sound in 2007. NY reported 100,000 bushels of clams and 25,000 bushels of oysters harvested from the Sound. Taken together, this represents approximately 37 million lbs of shellfish on a wet weight basis. The current harvest estimates are smaller than, but of similar magnitude to, the current population estimates used for model calibration purposes and provide a level of verification on the adequacy of the data underlying the calibration. It would be problematic if current harvest estimates were larger than population estimates.

SWEM as originally developed for eutrophication modeling, description provided above, was modified for the biomass harvesting assessment so that it could be applied to forecast the dissolved oxygen benefits, in concept, associated with implementing seaweed farming and shellfish aquaculture practices in Long Island Sound (see Section 2.3).

2.3 SWEM Biomass Harvesting Implementation

2.3.1 SWEM Shellfish Biomass Harvesting Implementation

Shellfish function to reduce nutrients and abate hypoxia in two ways. First, the shellfish assimilate a large percentage of what they consume. Thus, shellfish present in Long Island Sound and then removed from the Sound could serve the purpose of extracting organic particle bound nutrients based on what they assimilate. Rates of shellfish (primarily oysters) assimilation efficiency, averaging 0.75, have been reported by other researchers: Tenore and Dunstan, 1973; Valenti and Epifanio, 1981; Langefoss and Maurer, 1975 as cited in Powell et al. 1992 and Cerco and Noel 2007; 0.90 for phytoplankton carbon and 0.65 for detritus from data supporting MUSMOD (Newell et al., 1998); and 0.67 as used by HydroQual for suspension feeder bivalve modeling in Jamaica Bay.

Second, because of filter-feeding from the water column, shellfish play a role in focusing where and when organic particle bound nutrients from the water column not assimilated reach the sediment bed. This second process has previously been modeled empirically as an enhanced settling rate in SWEM. Shellfish aquaculture in Long Island Sound may be inclusive of oysters, blue mussels, and clams as well as other species. The enhanced settling rate is more properly referred to as a clearance rate or filtration rate. Powell et al. (1992) extensively reviewed laboratory-based size specific estimates of bivalve filtration rates, noting a bimodal distribution in the shellfish organism size to filtration rate relationship. Equations developed by Powell for high-gear and low-gear filtration rate roughly bracket the relationships used to define filtration rates by other researchers (Coughlan 1969; Doering and Oviatt 1986; and Gerritsen et al. 1994).

Working for the U.S. Army Corps of Engineers on the development of the Chesapeake Bay Environmental Model Package (HydroQual, 2000), HydroQual re-analyzed Powell's data by linear regression of a log-transformation of the data to obtain power functions for filtration rate per individual based on individual length. Ultimately, linear relationships for the log-transformed data of Powell developed by HydroQual for several organisms in Chesapeake Bay were based on

Powell's low-gear rate equation. SWEM's development and calibration, however, used a high-gear rate equation, but for relatively low efficiency organism, *Rangia* (as opposed to *Corbicula* or *Macoma* which filter almost twice as much). For the preliminary Long Island Sound investigation, the high-gear rate equation from the SWEM calibration was used. The filtration rate used in SWEM for organisms at aquaculture density in Long Island Sound is 0.033 m^3 g^{-1} shellfish C d^{-1} at 20^oC. This filtration rate corresponds to a clearance rate of 16.5 m d^{-1}.

Since HydroQual's work for the U.S Army Corps of Engineers on the initial development of the CBEMP, Cerco and Noel 2007 report a maximum filtration rate of 0.55 m^3 g^{-1} oyster C d^{-1} observed for oysters (Jordan 1987, Newell and Koch 2004) and modeled with the current CBEMP at a 27^oC temperature. The observations and CBEMP oyster modeling range from 0 to 0.55 m^3 g^{-1} oyster C d^{-1} with much of the data and CBEMP oyster modeling below 0.1 m^3 g^{-1} oyster C d^{-1}, especially when suspended solids are below 10 g m^{-3} as would be characteristic of Long Island Sound. At 20^oC, the CBEMP upper limit drops to 0.26 m^3 g^{-1} oyster C d^{-1} and much of the data and CBEMP oyster modeling is below 0.048 m^3 g^{-1} oyster C d^{-1} for suspended solids less than 10 g m^{-3}. The corresponding CBEMP clearance rate is 24 m d^{-1} when solids are less than 10 g m^{-3}. This suggests that the SWEM clearance rate for Long Island Sound, 16.5 m d^{-1} , is within range, but somewhat conservative (i.e. low).

In order to apply SWEM to demonstrate the oxygen benefits of shellfish aquaculture, SWEM was specifically modified to include:

- Revised source code so that only non-assimilated water column particles are removed from the water column and deposited in the sediment bed per the empirical filtration/clearance relationship. The other particles, representing shellfish assimilation efficiency, were tracked in SWEM as shellfish extraction terms for each of particulate organic carbon, nitrogen, phosphorus, and silica.
- An assimilation efficiency of both 0.75, the average of literature reporting and for sensitivity and testing purposes, 0.65, on the low end of literature reporting.
- A filter-feeding shellfish organism harvest density typical of productive aquaculture operations. Specifically, the density assigned is 500 gm of biomass as carbon per m^2 based on the work of Newell 1990 as cited in Newell 1998 for a harvest upper limit for a productive bottom mussel site in Maine. This density is not dissimilar from that cited by Lindahl et al. 2005 for 3-D mussel lines in Sweden. If adjusted for depth, the mussel density on the 3-D lines is 700 gm as carbon per m^2.
- The 500 gm of biomass as carbon per m^2 density was applied (1)across the entire Long Island Sound response regions 2 through 10 and (2) in those areas of Long Island Sound designated by CT and NY as approved for shellfish harvesting and less than 50 feet deep. These areas are shown on Figure 2.

An assumption implicit in the SWEM calculations is that it is assumed that the shellfish deliberately placed in Long Island Sound for harvesting purposes will continually be at an optimized asymptotic mass per unit area, or carrying capacity, at any given site. In reality, the harvesting operation would have to work out the logistics of achieving and maintaining maximized shellfish growth. SWEM was not used in this effort to model or predict the growth of the shellfish. Such an effort may be carried out under potential next steps described in Section 5.

2.3.2 SWEM Seaweed/Kelp Biomass Harvesting Implementation

Previously, the functioning of seaweed, or other macro-algae such as kelp, in consuming inorganic nutrients had not been considered in SWEM. Now, SWEM includes inputs of time variable inorganic nutrient loss rates due to seaweed at various locations based on user-specified seaweed density and seaweed nutrient stoichiometry. A limitation of this approach is that SWEM will not be used to model or predict the growth of the seaweed.

An assumption in the SWEM calculations is that the harvesting operation would have to work out the logistics of achieving and maintaining maximized seaweed growth. As an example, as identified in He at al., *Porphyra* requires less than 40 days from seeding to first harvest and can be harvested repeatedly every 15 days in net culture.

Kinetics were developed in SWEM for calculating empirically nutrient extraction rates on a grid cell specific basis based upon user inputted seaweed densities in mass per area units. By multiplying by depth, these densities were converted to mass seaweed per volume units. A number of density estimates were available. Self-shading effects of the biomass were also included in the SWEM calculations. Light attenuation beneath seaweed/kelp farms was increased in SWEM to mimic the shading effects of the seaweed and the reduction in light available for phytoplankton.

Seaweed stoichiometry was determined from typical values in the literature (e.g., *Ulva* is 3.5% N from Merrill et al.; *Laminaria* is 3-5% nitrogen from Gerard; *Porphyra* is 6.3% nitrogen dry weight from He et al.; Porphyra nitrogen concentrations close to 7% dry weight from Carmona et al.; Chung et al. present a hyperbolic relationship for predicting tissue nitrogen content between 2% and 5% as a function of ambient dissolved inorganic nitrogen concentration; Kim et al tabulate carbon and nitrogen as percentages of dry weight for four species of *Porphyra* under various nutrient and temperature conditions, generally 35-40% for carbon and 2-7% for nitrogen; Per C. Yarish, personal communication, ongoing research in Potugal reports 8% tissue nitrogen for *Gracilaria* grown in a high dissolved inorganic nitrogen effluent stream of finfish aquaculture and 3-4% tissue nitrogen has been reported in coastal ponds in Rhode Island; From Gerard, dry content of *Laminaria* is about 20%) so that mass seaweed can be converted to mass nutrients removed over the selected growing season. In the Chinese sea, for example, *Porphyra* farming resulted in a 50-94% reduction in ambient ammonia nitrogen concentrations (He et al., 2008) and 70-100% in a northeast American experimental setup (Carmona et al., 2006).

The seaweed/kelp stoichiometry included in SWEM calculations is: 5% N (Gerard, 1992 has reported that *Laminaria* are 3 to 5% nitrogen), 1% P, 40% carbon (Kim et al. reports 35-40% carbon for seaweed/kelp), carbon to chlorophyll ratio of 100, 10% fresh weight organism density to dry weight conversion factor, and dry weight to carbon conversion factor of 1/2. The species targeted in the SWEM simulations include: *Saccharina* (formerly *Laminaria*) for September to May and *Gracilaria* for May through November.

Seaweed/kelp was considered in SWEM as both a near bottom system and long-line photic zone system. For the near bottom system, SWEM simulated placement was restricted to portions of Long Island Sound Response Regions 2 thru 10 with light at six feet above bottom reaching 300 uE/m^2/sec.at least 70% of the time during daylight hours. This included 5 SWEM grid cells located in Response Regions 4, 3, and 2, in the area around the Norwalk Islands ([44, 47], [44, 48]), Oyster Bay ([38, 50], [39, 50]), and Hempstead Harbor ([40, 52]), with a surface area of 22.7 km^2 or approximately 4242 football fields. The organism density simulated with SWEM for the near bottom system is 2000 g DW per sq. m supported by the findings for *Laminaria* of Buck and Buchholz, 2004 (2000 g DW per sq. m) and Egan and Yarish, 1990 in Merrill et al., 1992 (2400 to 4700 g DW per sq. m).

Seaweed/kelp long-lines were evaluated in SWEM with a placement 1-2 feet below the water surface. Locations for long-line placement were identified based on SWEM calculations of high levels of dissolved inorganic nitrogen in water depths less than 50 feet where shellfish and near bottom kelp systems haven't been proposed. This includes SWEM grid cells in Little Neck Bay ([38, 53], [38, 54], [38, 55], [39, 56]) and Eastchester Bay ([38, 62], [39, 62], [39, 63], [39, 64]) with a surface area of 10.3 km^2, or approximately 1923 football fields. The organism density used in SWEM for the long-line system is 300 g DW per sq. m based on the work with *Laminaria* of Duarte et al., 2003.

It is noted that no attempt was be made to estimate existing natural seaweed/kelp densities for SWEM purposes. An inclusion of the natural population in SWEM would be somewhat flawed (i.e., overly optimistic) because the mostly empirical model code being developed assumes a harvesting removal mechanism that doesn't exist for the natural populations and ignores the in-situ senescence and die-off that natural populations would be subjected to.

An important consequence of the seaweed nutrient removal that SWEM captures mechanistically is that less nutrients are available to fuel phytoplankton growth as a result of the competing seaweed/kelp uptake of dissolved inorganic nutrients and removal of seaweed/kelp and absorbed nutrients. An important element of the competition between seaweed/kelp and phytoplankton for dissolved inorganic nutrients will be placing the seaweed/kelp at the edges of the Sound to intercept dissolved inorganic nutrients before they can reach phytoplankton in the main open waters. Seaweed/kelp placement may also be modeled in the future at any location in the entire Sound for nutrient uptake purposes.

2.4 SWEM SIMULATIONS

Several SWEM simulations have been completed which:

- Test the new SWEM shellfish code (i.e., 0% assimilation efficiency and current shellfish density reproduces the results of the original SWEM code)
- Assess model sensitivities to shellfish assimilation efficiencies (75% and 65%) and shellfish densities (current and aquaculture) throughout Response Regions 2 through 10.
- Assess responses to placement of shellfish throughout Response Regions 2 through 10 vs. in waters approved for shellfishing.
- Assess responses to shellfish placement in approved waters and kelp placement in near bottom waters with the requisite light.
- Assess responses to shellfish placement in approved waters, kelp placement in near bottom waters with the requisite light, and kelp placement in the photic zone of high dissolved inorganic nitrogen locations.

The SWEM estimates of the dissolved oxygen benefits of shellfish aquaculture by itself and in combination with seaweed/kelp aquaculture are available. The shellfish case with 75% assimilation efficiency was used for kelp evaluations. The consideration of extractive shellfish and seaweed aquaculture benefits simultaneously is consistent with integrated multi-trophic aquaculture (IMTA) approaches to sustainability, as well as polyculture (Chung et al. 2002). Subtraction can be used to approximate the seaweed aquaculture dissolved oxygen benefit independent of the shellfish aquaculture benefit, if necessary, but it is better to consider the two as coupled synergistic processes. There is documentation of an approximately 50% increase in seaweed and mussel production when co-cultivated (Kraan, 2008). While the synergy is not fully captured in the SWEM evaluation, it is still appropriate to consider both simultaneously.

Following previous Long Island Sound Study modeling work, the SWEM simulations of aquaculture were implemented under the loading conditions of the current nitrogen TMDL and consider 1988 and 1989 hydrological conditions.

3.0 RESULTS & DISCUSSION

SWEM outputs for the shellfish and kelp simulations were assessed in terms of improvements in minimum dissolved oxygen; improvements in living marine resource metrics, survival volume days and biomass volume days; and attainment of water quality standards for dissolved oxygen.

3.1 Improvements to Minimum Dissolved Oxygen

SWEM results suggest that minimum dissolved oxygen can be improved throughout the majority of Long Island Sound by as much as 2 mg/L. Calculated dissolved oxygen minima resulting from shellfish and seaweed aquaculture simulations are largely greater than 3.5 mg/L throughout the Sound. 3.5 mg/L of dissolved oxygen would be fully protective of the survival of the juveniles and adults of sensitive marine species (e.g., mud crab). These results are displayed on the Figures in Appendix A. The Figures in Appendix A include spatial displays on a color scale of minimum dissolved oxygen for the implementation of the nitrogen TMDL both with and without the various bio-extraction cases considered. Results are presented as both resulting dissolved oxygen concentrations and as differences in dissolved oxygen concentrations. Also presented in Appendix A are SWEM results for the nitrogen concentrations corresponding to the minimum dissolved oxygen concentrations. Coincident total nitrogen concentrations can be reduced by 0.15 mg/L.

As shown in Appendix A, results of the shellfish alone scenario achieve improvements in dissolved oxygen minima up to 1.5 mg/L. Near bottom placement of seaweed/kelp where sufficient light is available would add another 0 to 0.3 mg/L of dissolved oxygen minima improvements based on SWEM results. Photic zone seweed/kelp addition could add another 0 to 0.3 mg/L of minimum dissolved oxygen improvement based on the scenario simulated.

3.2 Improvements to Site Specific Living Marine Resources Metrics

In addition to looking at changes in minimum dissolved oxygen concentrations, expected ecological responses, mortality-volume-DO days and biomass reduction-volume-DO days in the Sound were examined. These results are presented in Appendix B. Mortality-volume-DO days and biomass reduction-volume-DO days are defined based on the 1996 work of the Long Island Sound Living Marine Resources Workgroup (LMRWG). The LMRWG identified expected reductions in organism survival and biomass for various DO intervals for Long Island Sound based on measured data. SWEM results have been processed to track the "volume x days" in the Sound at various dissolved oxygen intervals with survival and biomass impacts.

The ecological responses presented in Appendix B, on a Sound-wide basis, suggest that the greatest reductions in mortality and biomass impairments on a DO-volume-days basis are realized when loadings are reduced from baseline conditions (shown in gray) to the mandated Phase 3 and 4 TMDL conditions with expected carbon loading reductions (shown in green), (i.e., about 69% and 90% for mortality and biomass, respectively). Although pastoral loading conditions would almost entirely eliminate any mortality and biomass impairment on a DO-volume-days basis (shown in black), large and costly intermediate loading reductions between TMDL conditions and pastoral conditions that we tested previously with SWEM simulations (i.e., 75% atmospheric nitrogen deposition reduction and high level runoff reductions with 3 mg/L STP TN effluents) are expected to produce relatively modest reductions in mortality and biomass impairment (shown in red and pale blue). Shellfish and seaweed/kelp aquaculture in conjunction with the mandated Phase 3 and 4 TMDL conditions with expected carbon loading reductions (as modeled) have greater reductions in mortality and biomass impairment (shown in orange, bright blue and yellow) than the large and potentially more costly loading reductions tested previously.

Specifically, the combined shellfish and seaweed/kelp aquaculture with mandated TMDL case (shown in yellow) eliminates all mortality volume days associated with the occurrence of dissolved oxygen less than or equal to 4 mg/L and leaves only 16% of the total mortality volumes days (associated with dissolved oxygen between 4 and 5 mg/L) under the more severe 1988 hydrological conditions tested. For biomass volume days, each of the three aquaculture scenarios evaluated would eliminate all (i.e., 100%) impairment for either of the two hydrological conditions tested. SWEM results demonstrate that the high loading reductions cases were not as successful as the aquaculture cases (i.e., 95-98% reduction with impairments still remaining for dissolved oxygen between 2 and 4 mg/L).

3.3 Improvements to Dissolved Oxygen Standards Attainment

The States of New York and Connecticut promulgate numeric water quality standards that are applicable to the waters of Long Island Sound. These standards are summarized in Table 1. The currently mandated TMDL for nitrogen loadings to Long Island Sound would not result in full attainment of these standards based on SWEM calculations. Expected non-attainment for the current TMDL includes:

- The NY chronic standard would not be attained in Long Island Sound Response Regions 1 to 7.
- The NY acute standard would not be attained in Long Island Sound Response Regions 1 to 5.
- The CT acute standard would not be attained in Long Island Sound Response Regions 1 to 5.
- The CT chronic standard would not be attained in Long Island Sound Response Regions 1 to 8.
- The CT above pycnocline standard would not be attained anywhere in Long Island Sound.

CTDEP is revising its dissolved oxygen standards for Long Island Sound to improve attainment consistency across Long Island Sound while maintaining protection of marine resources. However, since CT and NY interpretation of their standards varies, the degree of compliance and noncompliance will still continue to differ somewhat between each States' waters. For this reason, SWEM outputs for biomass harvesting in Long Island Sound have been compared to current standards in each of the states and the NY standards applied to both NY and CT waters. CT's standards revision will have multiple implications:

- A relaxed standard for dissolved oxygen between 3.5 mg/L and 3.0 mg/L below the pycnocline.
- A potentially tougher standard for dissolved oxygen between 3.5 and 4.8 mg/L below the pycnocline.
- A relaxed standard above the pycnocline.

Results are reported on a days of non-attainment basis in Appendices C & D for the shellfish aquaculture case, the shellfish aquaculture plus near-bottom seaweed/kelp case, and the combined shellfish aquaculture and the near-bottom and photic zone seaweed/kelp farming cases. As shown in Appendices C and D, the New York State chronic standard can be attained throughout Long Island Sound waters in Response Regions 3 through 10 with major portions of the waters in Response Regions 1 and 2 also in attainment. If CT standards are retained (refer to Appendix D), marginal non-attainment would be expected in north-shore portions of Response Regions 3, 4, 6, and 10 related to the above pycnocline standard.

4.0 CONCLUSIONS

Shellfish aquaculture and seaweed/kelp harvesting appear to represent a promising mechanism for attaining dissolved oxygen standards in Long Island Sound based on SWEM calculations. SWEM results show that the NY chronic standard would be met throughout Long Island Sound Response Regions 3 through 10 and large portions of Response Regions 1 and 2 with shellfish aquaculture and seaweed farming applied under current TMDL loading conditions. SWEM results demonstrate that shellfish aquaculture and seaweed/kelp harvesting are likely more effective than additional reductions to nitrogen loadings, beyond those already mandated by the existing nitrogen TMDL, for purposes of attaining dissolved oxygen standards and meeting other living marine resources objectives. While the incorporation of shellfish and seaweed/kelp nitrogen removal mechanisms into SWEM was done quantitatively and in a scientifically defensible manner, future funding should be directed at incorporating shellfish and seaweed/kelp functioning more comprehensively into SWEM to further substantiate these findings and to have greater predictive capabilities to support future design and installation considerations. Shellfish aquaculture and seaweed/kelp harvesting may be similarly evaluated in other urban estuaries, such as the NY/NJ Harbor, in which dissolved oxygen standards are not fully attained.

5.0 NEXT STEPS

The work outlined above was intended to provide a preliminary quantitative estimate of the potential changes in Long Island Sound dissolved oxygen that could result from a concerted effort to implement shellfish and seaweed/kelp aquaculture operations in the future. Given the success of the results, it is advisable to enhance the modeling work and implement a more mechanistic approach to modeling shellfish and kelp in SWEM, similar to the mechanistic approach already taken in SWEM for modeling phytoplankton or in the CBEMP for modeling oysters.

Unlike SWEM's empirical bivalve water column clearance parameterization, CBEMP's mechanistic oyster kinetics directly include a full mass balance (i.e., source and sink terms with temperature and oxygen dependencies) around filter feeder biomass: filtration rate, excretion rate, assimilation rate, growth rate, respiration rate, predation rate, and hypoxia mortality rate. Future work might also include a consideration of particle concentration dependence and mass of particles previously filtered dependence on specifying filtration and respiration rates as suggested by mussel filtration rate and shell gape data from Mud Cove, Maine over a tidal cycle (Newell et al., 1998). Mechanistic shellfish modeling could be expanded to include separate kinetics for each of multiple species.

Incorporating mechanistic growth kinetics for seaweed/kelp inside a complex three-dimensional, time-variable coupled hydrodynamic and eutrophication model (i.e., SWEM) would be novel. As described in Duarte et al., hydrodynamic transport phenomena have typically been overly simplified in other ecological models applied to evaluate aquaculture. The model developed by Duarte et al. for aquaculture evaluation in Sungo Bay in the Shandong Province of China is two-dimensional. Additional considerations for more rigorous modeling of seaweed with SWEM should include:

- mechanistic growth kinetics for seaweed/kelp including temperature, nutrient and light limitations
- the decomposition in the sediment bed of seaweed/kelp biomass (mostly rapidly decomposing per Gerard) lost from the potential farm/harvest operations
- changes in physical and hydrodynamic features of the Sound related to potential seaweed/kelp farms such as reductions in vertical water column mixing associated with wind events, etc.
- further restraints on farm placement (i.e., public access, navigation, strength of currents, etc.)
- potential incorporation into SWEM of features from the AquaModel (http://aquamodel.org) or other numerical models commonly used in aquaculture applications
- potential collaboration with experts from the aquaculture modeling community. Such experts may include, per the recommendations of Charles Yarish, Roger Newell from the University of Maryland, Dale Kiefer from University of Southern California, and Jack Rensel from Rensel Associates in Arlington, WA.

6.0 ACKNOWLEDGEMENTS

The work contained herein was funded by a grant from the United States Environmental Protection Agency (EPA) Long Island Sound Office to the Hudson River Foundation. HydroQual, Inc. served as a contractor to the Hudson River Foundation. Technical review comments provided by Charles Yarish and Gary Wikfors in cooperation with the Long Island Sound Office were gratefully appreciated.

7.0 REFERENCES

Berner, R. A. 1964. An idealized model of dissolved sulfate distributions in recent sediments. Geochimica et Cosmochimica Acta (UK) 28:1497-1503.

Berner, R. A. 1974. Kinetic models for the early diagenesis of nitrogen, sulfur, phosphorus and silicon in anoxic marine sediments, p. 427-450. In E.D. Goldberg (ed.), The Sea, Vol. 5, Wiley.

Berner, R. A. 1980. Early Diagenesis. A Theoretical Approach. Princeton University Press, Princeton, NJ.

Blumberg, A.F., L.A. Khan, & J.P. St. John. 1999. Three-dimensional hydrodynamic model of New York Harbor region. *J. Hydr. Engrg., ASCE* 125(8): 799-816.

Blumberg, A.F., & G.L. Mellor, 1987. A description of a three-dimensional coastal ocean circulation model. In: N. Heaps, editor. Three-dimensional coastal ocean models. Coastal and estuarine sciences: Volume 4. Washington, D.C.: American Geophysical Union. pp. 1-16.

Buck, B.H. and C.M. Buchholz. 2004. The offshore-ring: A new system design for the open ocean aquaculture of macroalgae. *J. appl. Phycol.* 16: 355-368.

Carmona, R., G.P. Kraemer, and C. Yarish. 2006. Exploring Northeast American and Asian species of *Porphyra* for use in an integrated finfish-algal aquaculture system. *Aquaculture* 252: 54-65.

Cerco, C.F. and M.R. Noel. 2007. Can Oyster Restoration Reverse Cultural Eutrophication in Chesapeake Bay? *Estuaries and Coasts* 30(2):331-343.

Chung, I.K., Y.H. Kang, C. Yarish, G.P. Kraemer, and J.A. Lee. 2002. Application of Seaweed Cultivation to the Bioremediation of Nutrient Rich Effluent. *Algae* 17(3):187-194.

Coughlan, J. 1969. The estimation of filtering rate from the clearance of suspensions. *Marine Biology* 2:356-358.

Di Toro, D. M. and J. J. Fitzpatrick. 1993. Chesapeake Bay sediment flux model. Contract report EL-93-2. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Doering, P.H. and C.A. Oviatt. 1986. Application of filtration rate models to field populations of bivalves: an assessment using experimental mesocosms. *Mar. Ecol. Prog. Ser.* 31: 265275.

Duarte, P., R. Meneses, A.J.S. Hawkins, M. Zhu, J. Fang, and J. Grant. 2003. Mathematical modelling to assess the carrying capacity for multi-species culture within coastal waters. *Ecological Modelling* 168:109-143.

Egan, B. and C. Yarish. 1990. Productivity and life history of *Laminaria longicruris* at its southern limit in the Western Atlantic Ocean. Mar. Ecol. Prog. Ser. 67: 263-273.

Gerard, V.A. 1992. *Can Seaweed Farms Alleviate Hypoxia in Western Long Island Sound?* Submission to Long Island Sound Study Alternative Technologies Workshop.

Gerritsen, J., A.F. Holland, D.E. Irvine. 1994. Suspension-feeding bivalves and the fate of primary production: an estuarine model applied to Chesapeake Bay. *Estuaries* 17: 403-416.

He, P., S. Xu, H. Zhang, S. Wen, Y. Dai, S. Lin, and C. Yarish. 2008. Bioremediation efficiency in the removal of dissolved inorganic nutrients by the red seaweed, *Porphyra yezoensis*, cultivated in the open sea. *Water Research* 42: 1281-1289.

Hutchinson, G. E. 1967. A treatise on limnology, p. 306-354. In Introduction to Lake Biology and Limnoplankton, Vol. II, Wiley, New York.

HydroQual, Inc, 2000. *Development of a Suspension Feeding and Deposit Feeding Benthos Model for Chesapeake Bay*. Report prepared for the Chesapeake Bay Program's Modeling Subcommittee and the U.S. Army Corps of Engineers under contract DACW39-96-0001. July 2000.

HydroQual, 2007a. *A Model for the Evaluation and Management of Contaminants of Concern in Water, Sediment, and Biota in the NY/NJ Harbor Estuary. Hydrodynamic Sub-model.*. Report prepared for the Hudson River Foundation on behalf of the Contamination Assessment and Reduction Project (CARP).

HydroQual, 2007b. *A Model for the Evaluation and Management of Contaminants of Concern in Water, Sediment, and Biota in the NY/NJ Harbor Estuary. Sediment Transport/Organic Carbon Production Sub-model.* Report prepared for the Hudson River Foundation on behalf of the Contamination Assessment and Reduction Project (CARP).

HydroQual, Inc. 2001a. Newtown Creek Water Pollution Control Project East River Water Quality Plan / Task 10.0 System-Wide Eutrophication Model (SWEM) / Sub-Task 10.1 Construct SWEM. *Report prepared for the City of New York, Department of Environmental Protection-New York, New York under subcontract to Greeley and Hansen.* 75 pp.

HydroQual, Inc. 2001b. Newtown Creek Water Pollution Control Project East River Water Quality Plan / Task 10.0 System-Wide Eutrophication Model (SWEM) / Sub-Task 10.2 Obtain and Reduce Loading/Water Quality Data. *Report prepared for the City of New York, Department of Environmental Protection-New York, New York under subcontract to Greeley and Hansen.* 111 pp.

HydroQual, Inc. 2001c. Newtown Creek Water Pollution Control Project East River Water Quality Plan / Task 10.0 System-Wide Eutrophication Model (SWEM) / Subtask 10.4 Calibrate SWEM Water Quality / Subtask 10.6 Validate SWEM Water Quality. R*eport prepared for the City of New York, Department of Environmental Protection-New York, New York under subcontract to Greeley and Hansen.* 141 pp and appendices.

HydroQual, Inc. 2001d. Newtown Creek Water Pollution Control Project East River Water Quality Plan / Task 10.0 System-Wide Eutrophication Model (SWEM) / Sub-Task 10.6 Validate SWEM Hydrodynamics. *Report prepared for the City of New York, Department of Environmental Protection-New York, New York under subcontract to Greeley and Hansen.* 312 pp.

HydroQual, Inc. 2001e. Technical Memorandum – Response to: "Report on the Calibration and Validation of the System-Wide Eutrophication Model Hydrodynamic Model" by

Connecticut Department of Environmental Protection. *Report prepared for the City of New York, Department of Environmental Protection-New York, New York under subcontract to Greeley and Hansen*. 59 pp.

HydroQual, Inc. 2001f. Newtown Creek Water Pollution Control Project East River Water Quality Plan/ Task 10.0 System-Wide Eutrophication Model (SWEM)/Sub-Task 10.3 Calibrate SWEM Hydrodynamics. *Report prepared for the City of New York, Department of Environmental Protection-New York, New York under subcontract to Greeley and Hansen*. 261 pp.

Kim, J.K., G.P. Kraemer, C.D. Neefus, I.K. Chung, C. Yarish. 2007. Effects of temperature and ammonium on growth, pigment production, and nitrogen uptake by four species of *Porphyra* (Bangiales, Rhodophyta) native to the New England coast. *J. Appl. Phycol.* 19: 431-440.

Kraan, S. 2008. Integrated Multi-Trophic Aquaculture (IMTA) - the right move for sustainability? *Inshore Ireland.* June 2008. p. 20.

Landeck Miller, R.E., and J.P. St. John. 2006. Modeling Production in the Lower Hudson River Estuary. In: J.S. Levinton and J.R. Waldman(Eds.), *The Hudson River Estuary*, pp. 140-153. Cambridge, New York, NY.

Lindahl, O., R. Hart, B. Hernroth, S. Kollberg, L. Loo, L. Olrog, A. Rehnstam-Holm, J. Svensson, S. Svensson, nd U. Syversen. 2005. Improving Marine Water Quality by Mussel Farming - A Profitable Solution for Swedish Society. *Ambio* 34(2): 129-136.

Lund, J. W. G. 1965. The ecology of the freshwater phytoplankton. Biological Reviews of the Cambridge Philosophical Society. 40:231-293.

Merrill, J., J. Killar, X. Huang, and C. Yarish. 1992. *Aquaculture methods for use in managing eutrophicated waters.* In: Schubel, J.R. The Second Phase of an Assessment of Alternatives to Biological Nutrient Removal at Sewage Treatment Plants for Alleviating Hypoxia in Western Long Island Sound. Report of the Long Island Sound Study Alternative Technologies Workshop for the U.S. Environmental Protection Agency on 21-22 November 1991 Working Paper 56, Reference No. 91-19. 19p.

Newell, C.R., D.E. Campbell, and S.M. Gallagher. 1998. Development of the mussel aquaculture lease site model MUSMOD: a field program to calibrate model formulations. *J. Exp. Mar. Biol. Ecol.* 219:143-169.

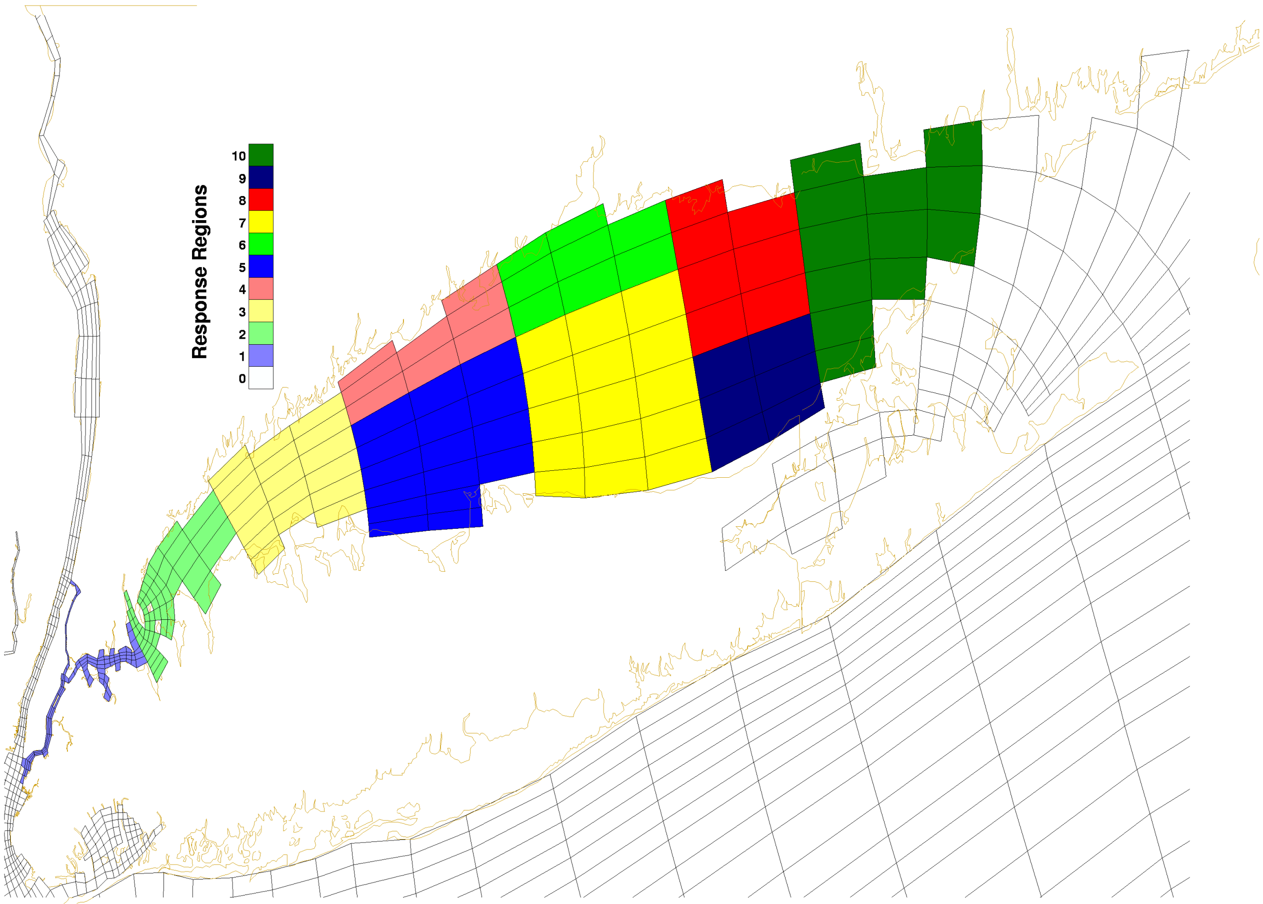
Powell, E.N., E.E. Hofmann, J.M. Klinck, and S.M. Ray. 2002. Modeling Oyster Populations I. A Commentary on Filtration Rate. Is Faster Always Better? *J. Shellfish Res.* 11(2):387-398.

Raymont, J. E. G. 1963. Plankton and Productivity in the Oceans. Pergamon Press, New York.

Rhee, G. Y. 1973. A continuous culture study of phosphate uptake, growth rate and polyphosphates in Secendemus sp. Journal of Phycology 9:495-506.

Steele, J. H. 1962. Environmental control of photosynthesis in the sea. Limnology and Oceanography 7:137-150.

Strickland, J. D. H. 1965. In J. P. Riley and G. Skivow (eds.), Chemical Oceanography, Production of Organic Matter in Primary Stages of the Marine Food Chain. Vol. 1, Academic Press, New York.

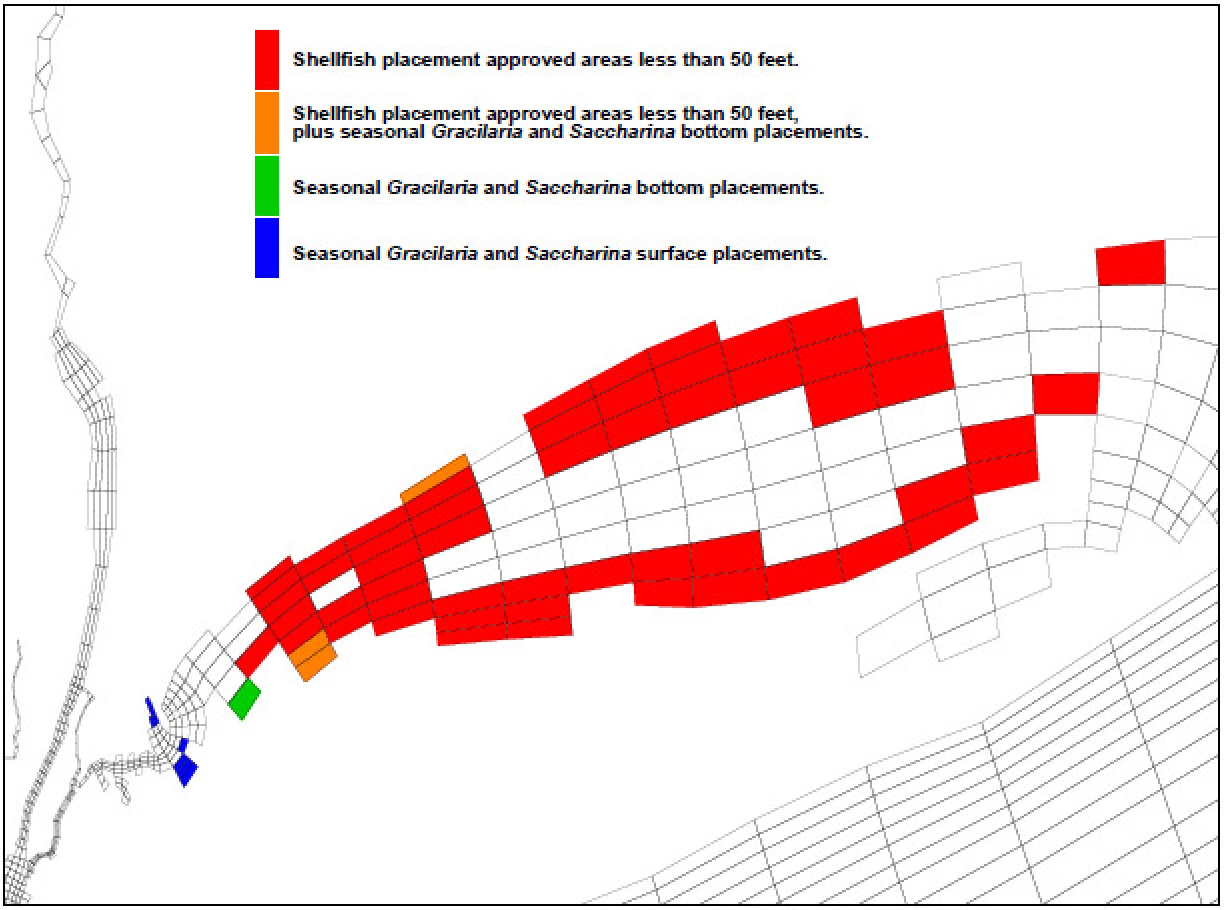


LIS 3.0 Response Regions mapped to SWEM grid

Figure 1

Table 1 – Dissolved Oxygen Standards Applicable to Long Island Sound

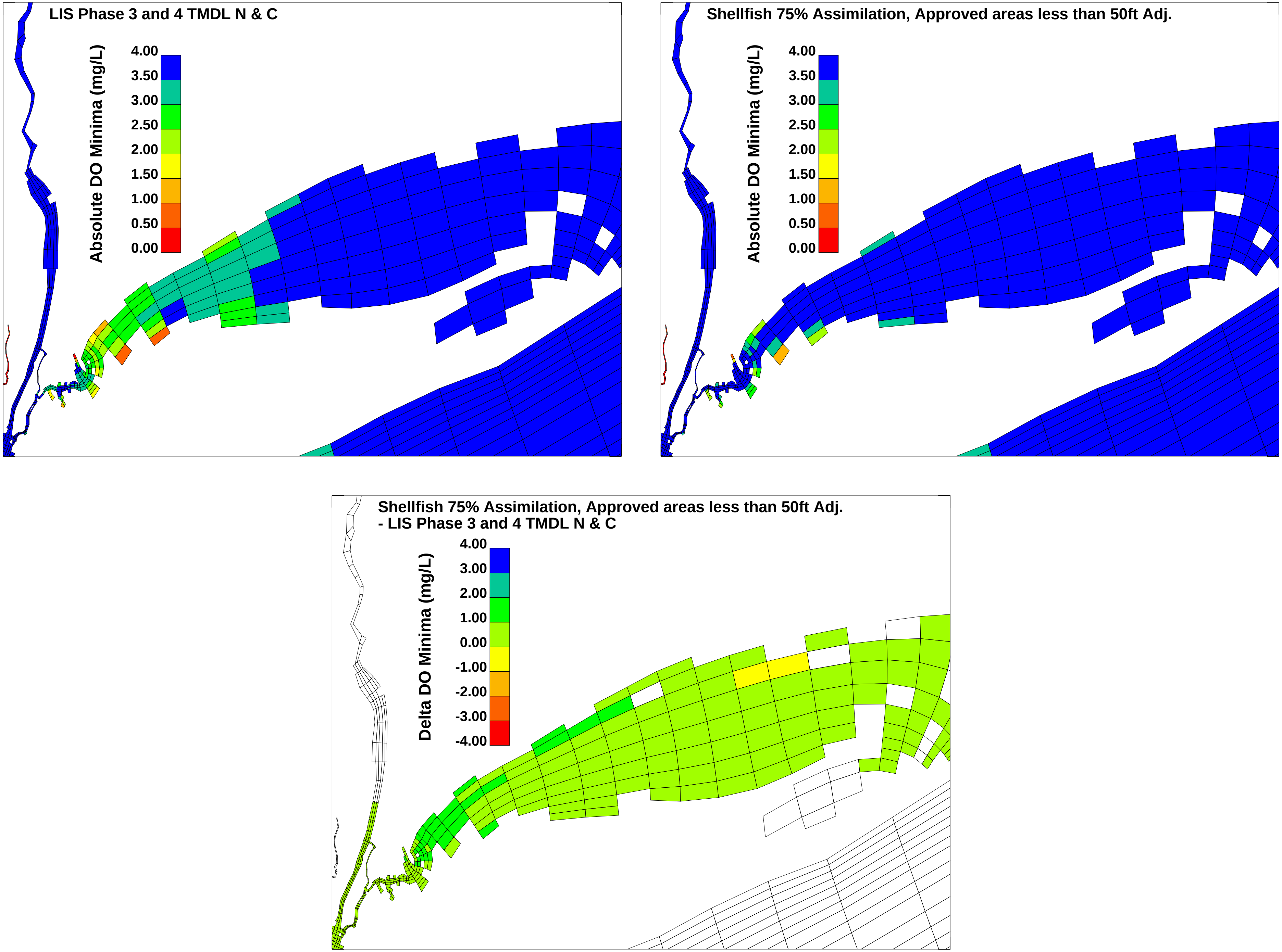
TYPE	CT	NY SA & SB (excluding class I)
above pycnocline	never < 6.0 mg/L	NA
Acute	never < 3.5 mg/L below pycnocline	never < 3.0 mg/L full depth
Chronic	3.5 to 4.8 mg/L: 3.5–3.8 mg/L 5 days 3.8–4.3 mg/L 11 days 4.3– 4.8 mg/L 21 days below pycnocline	3.0 to 4.8 mg/L: Days set in 0.1 mg/L increments with new cohorts every 66 days full depth



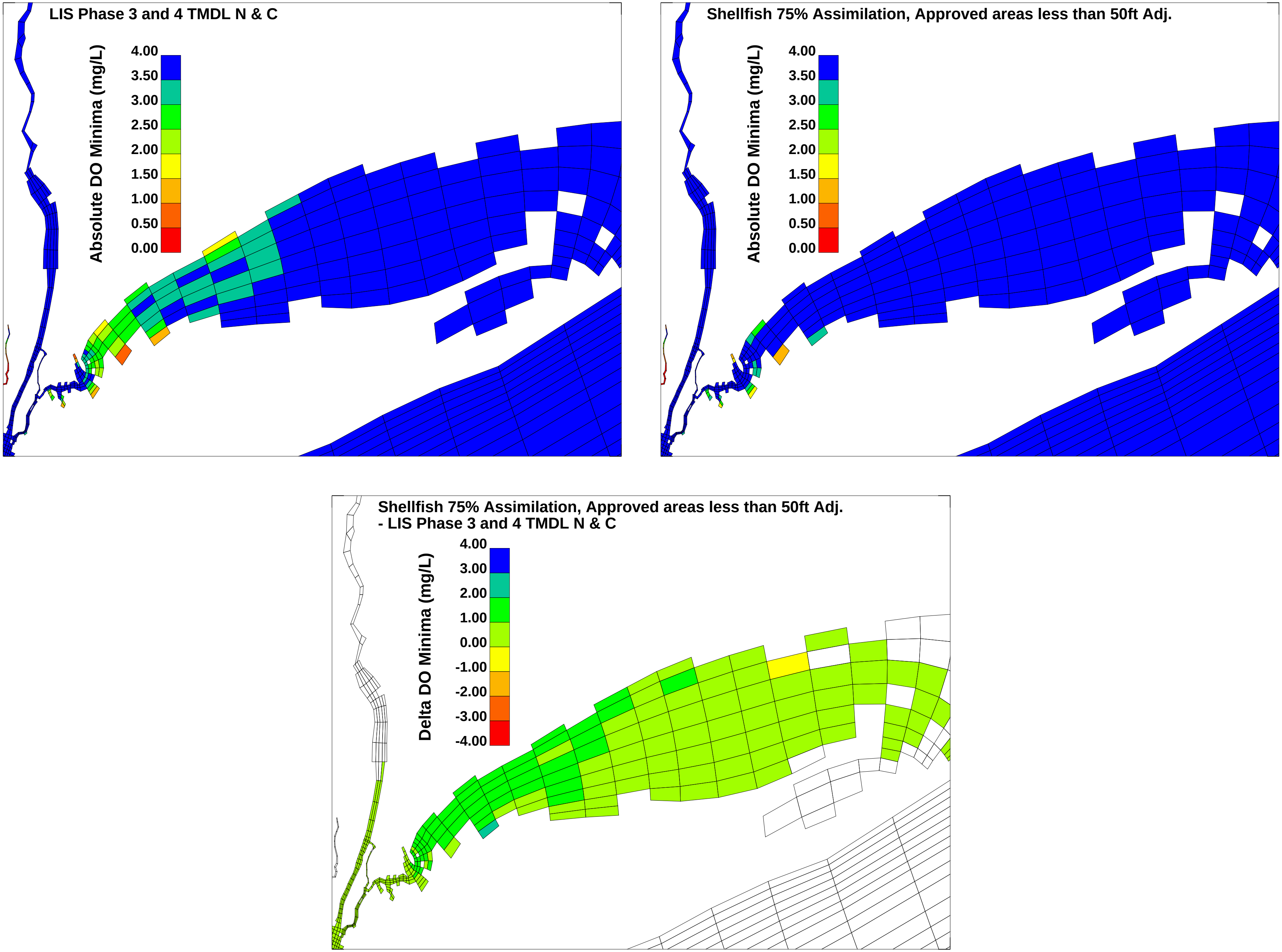
Cells for Aquaculture Placement

Figure 2.

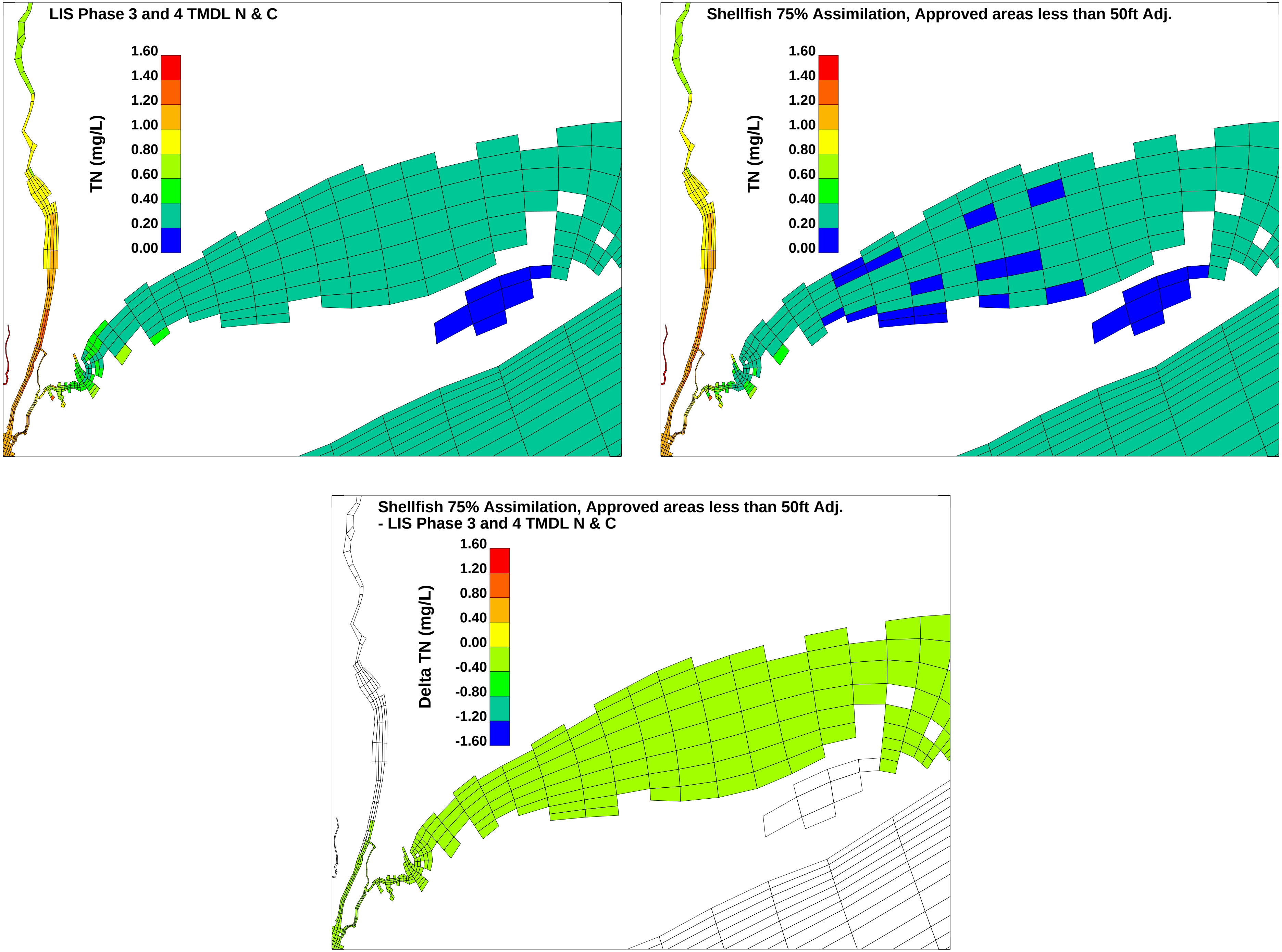
APPENDIX A
MAPS OF DISSOLVED OXYGEN MINIMA



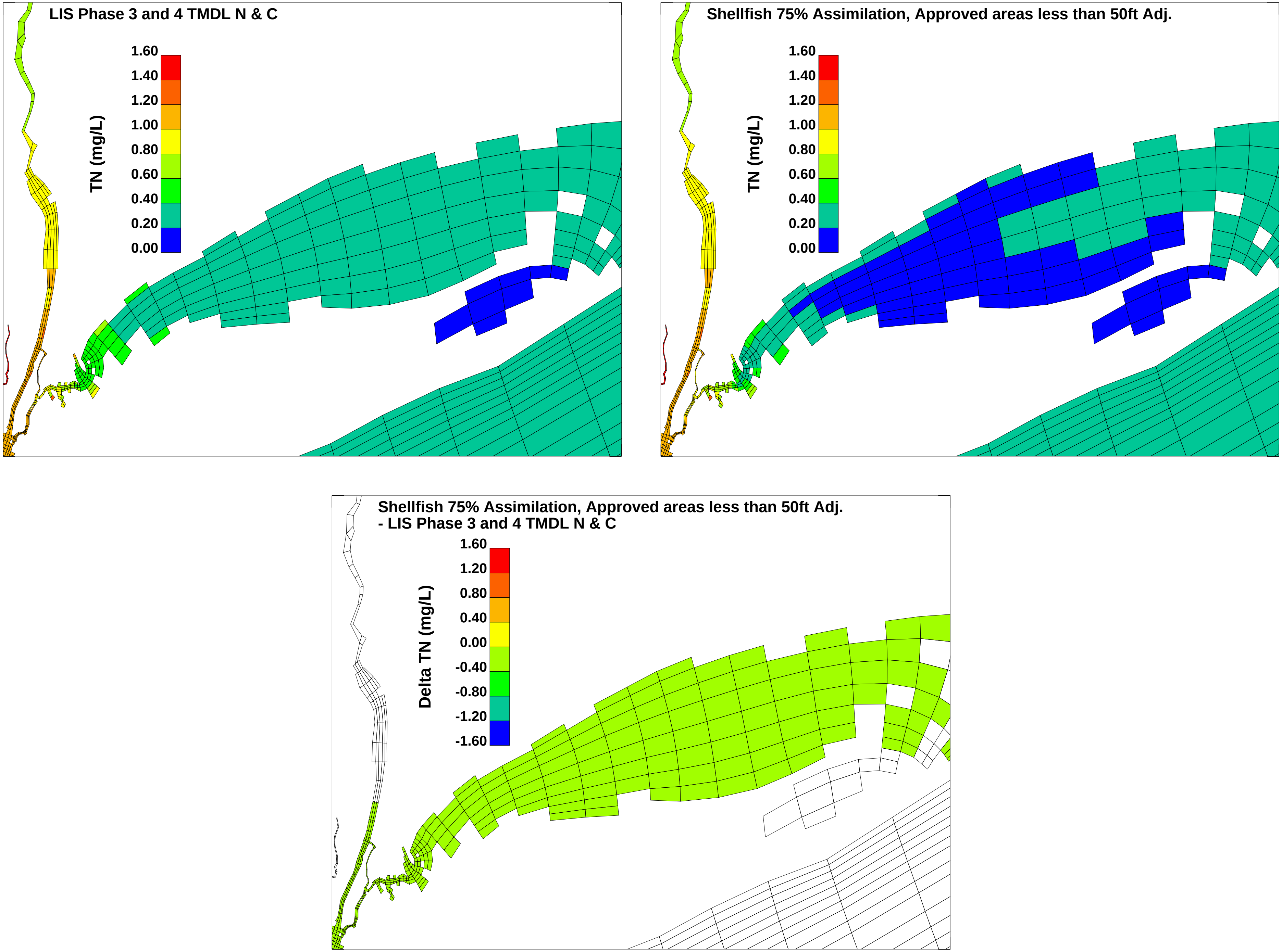
Absolute DO Minima, 1988 Hydrodynamic Conditions



Absolute DO Minima, 1989 Hydrodynamic Conditions



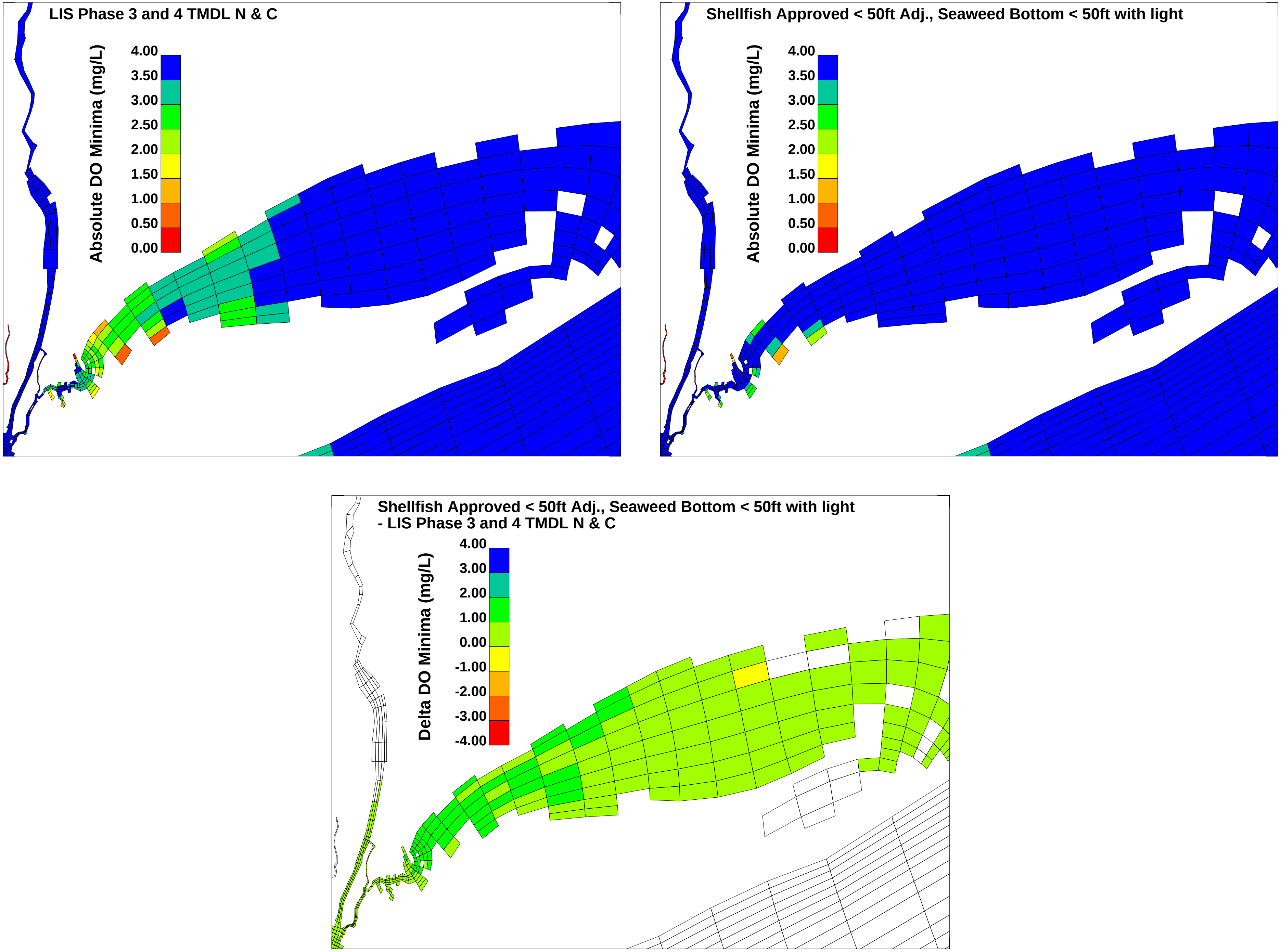
Total Nitrogen Corresponding to Absolute DO Minima, 1988 Hydrodynamic Conditions


LIS Phase 3 and 4 TMDL N & C

Shellfish 75% Assimilation, Approved areas less than 50ft Adj.

Shellfish 75% Assimilation, Approved areas less than 50ft Adj.
- LIS Phase 3 and 4 TMDL N & C

Total Nitrogen Corresponding to Absolute DO Minima, 1989 Hydrodynamic Conditions



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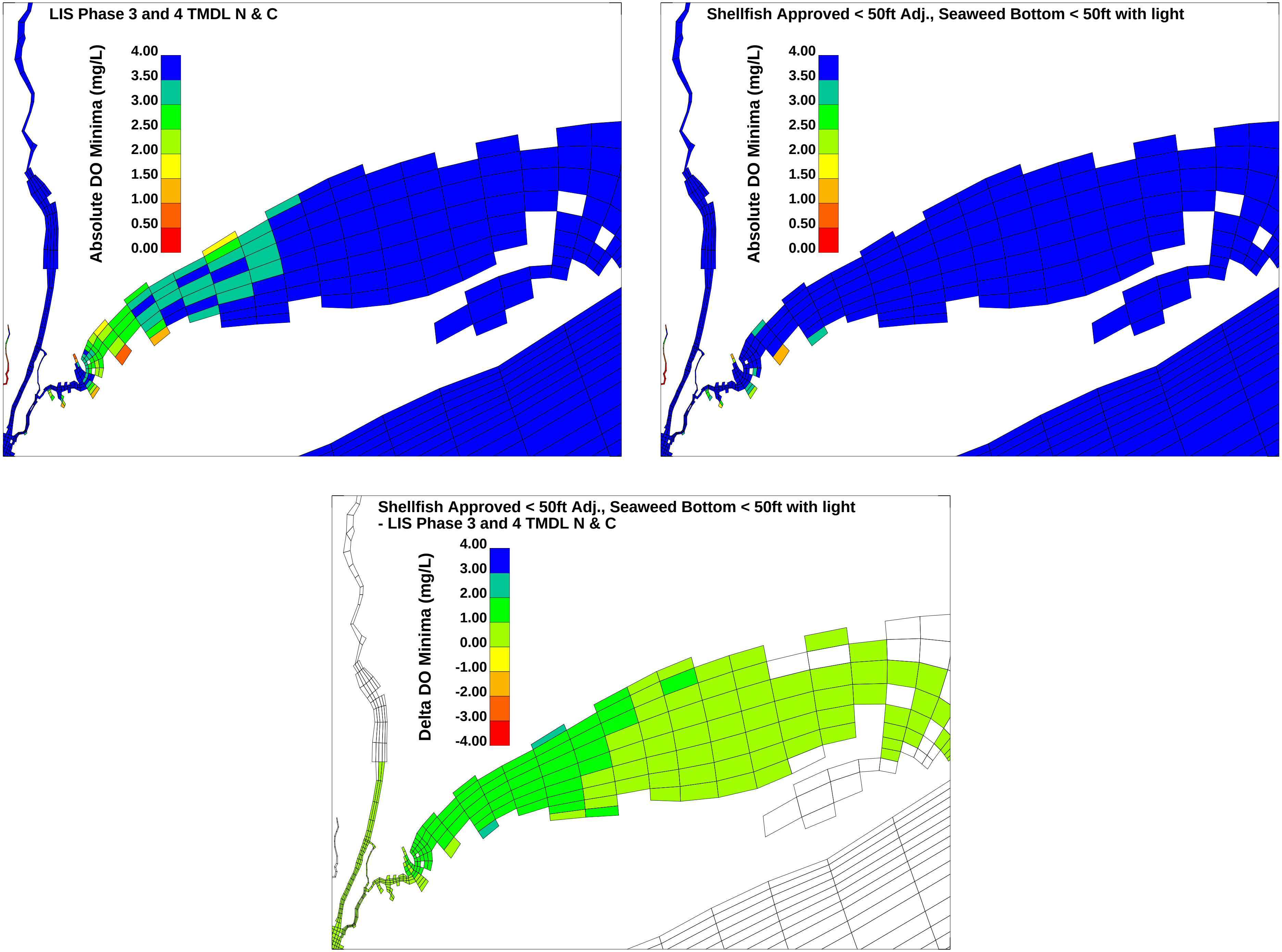
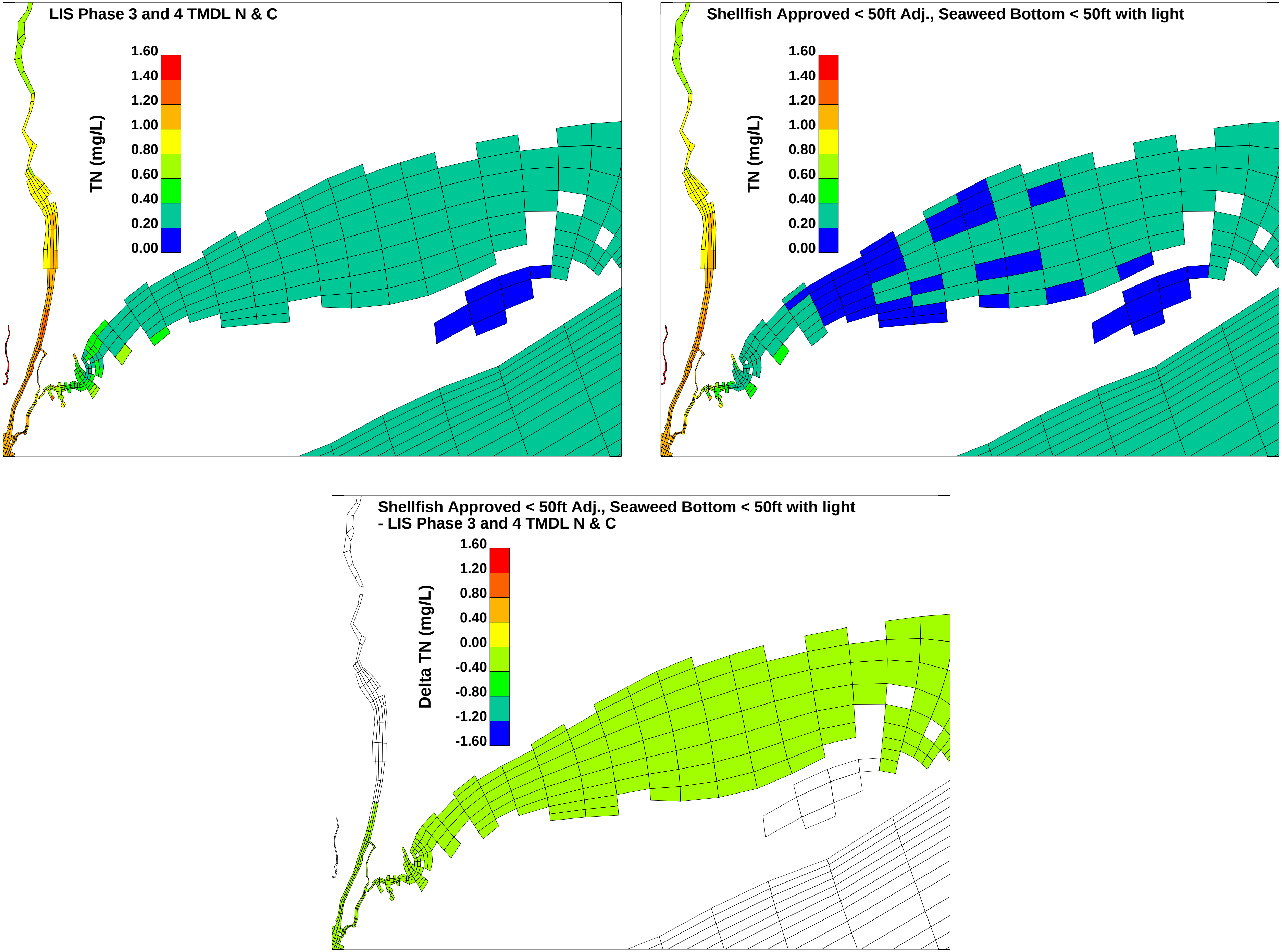

LIS Phase 3 and 4 TMDL N & C

Shellfish Approved < 50ft Adj., Seaweed Bottom < 50ft with light

Shellfish Approved < 50ft Adj., Seaweed Bottom < 50ft with light - LIS Phase 3 and 4 TMDL N & C

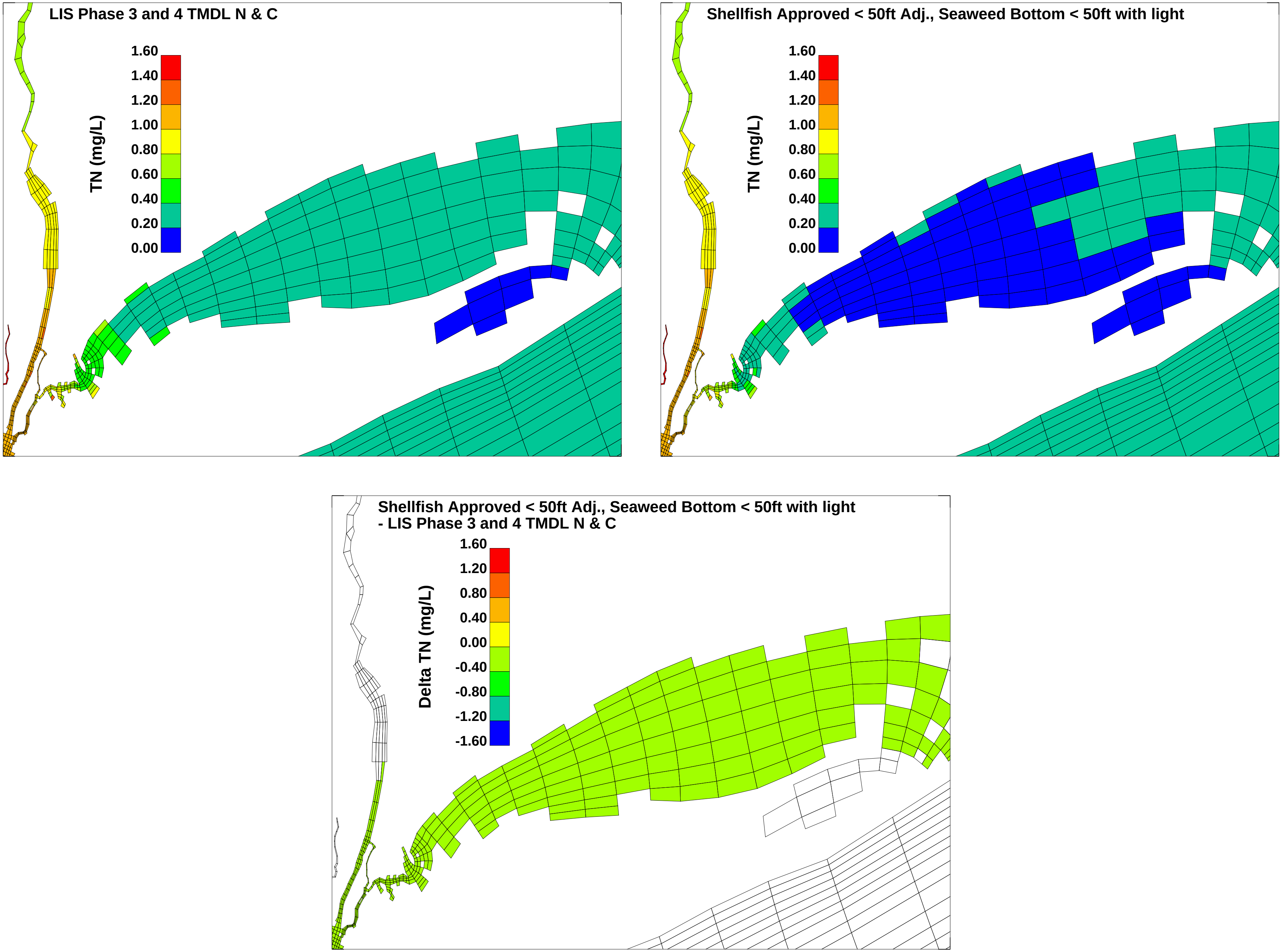
Absolute DO Minima, 1989 Hydrodynamic Conditions


LIS Phase 3 and 4 TMDL N & C

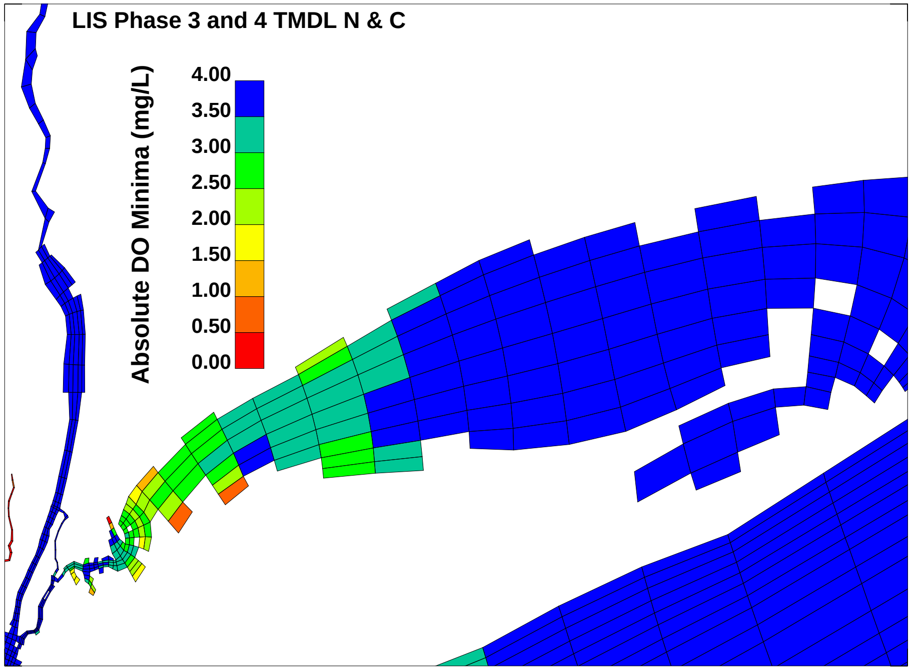
Shellfish Approved < 50ft Adj., Seaweed Bottom < 50ft with light

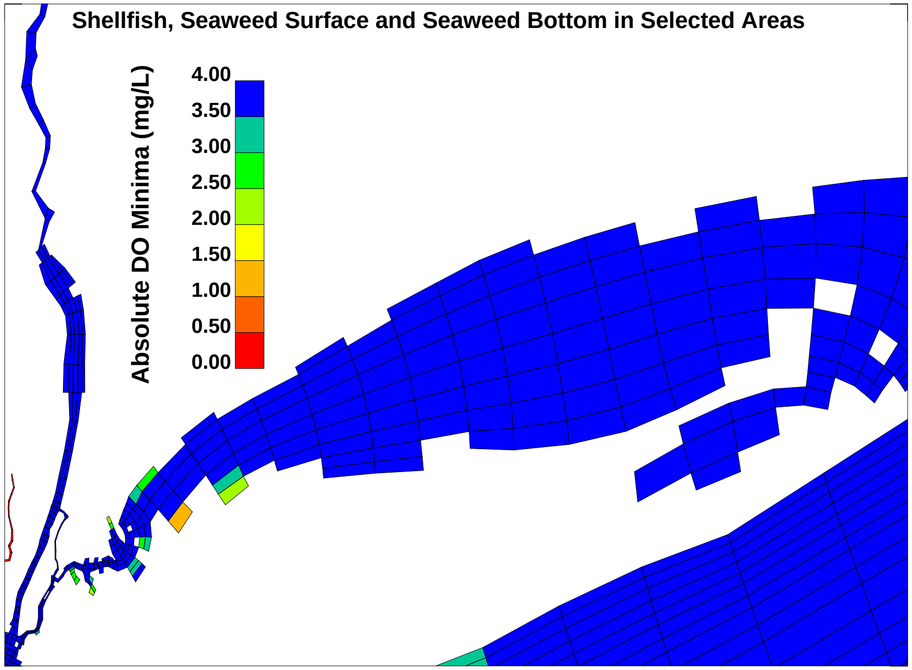
Shellfish Approved < 50ft Adj., Seaweed Bottom < 50ft with light
- LIS Phase 3 and 4 TMDL N & C

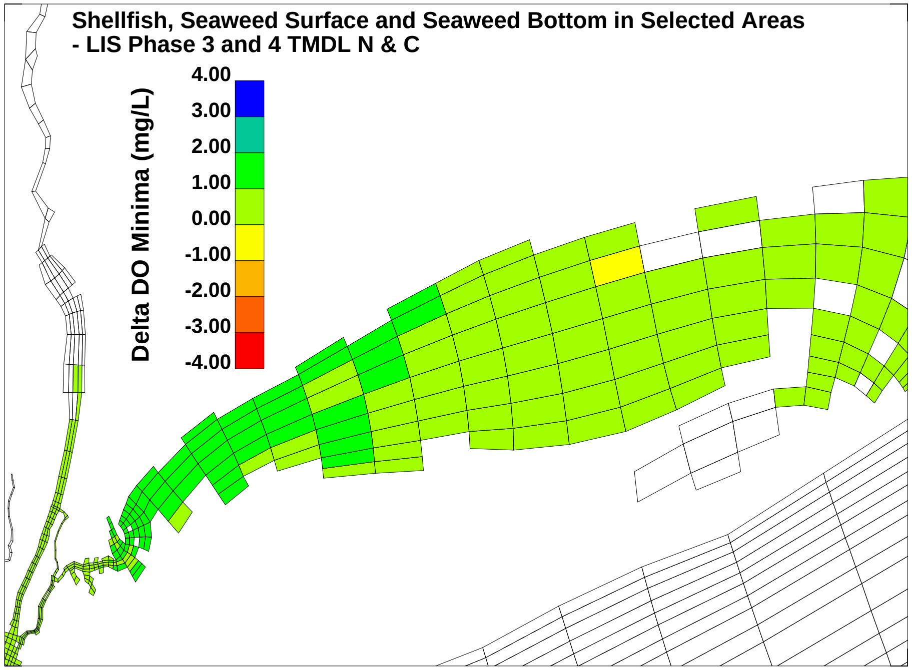
Total Nitrogen Corresponding to Absolute DO Minima, 1988 Hydrodynamic Conditions



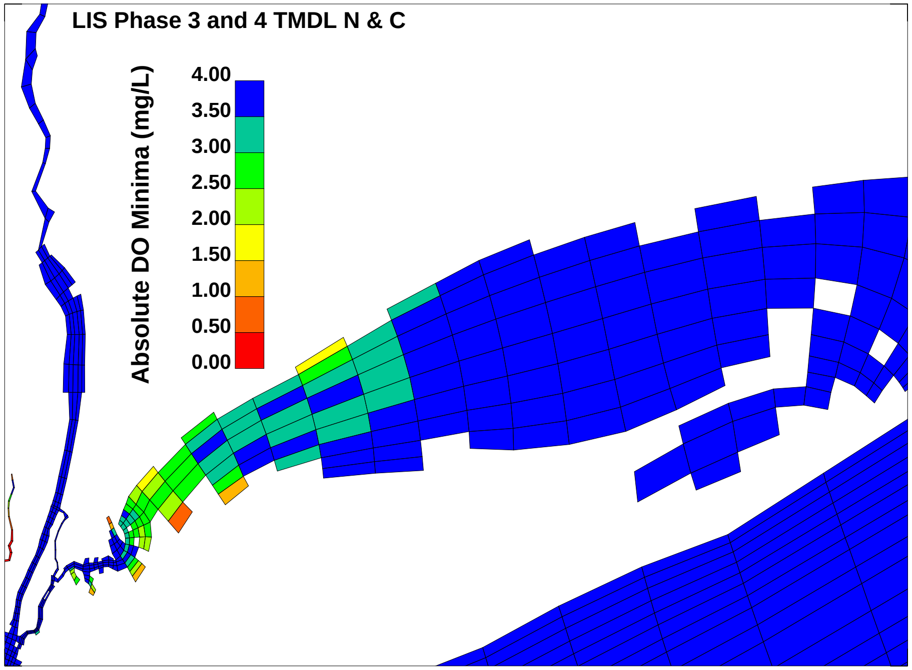
Total Nitrogen Corresponding to Absolute DO Minima, 1989 Hydrodynamic Conditions

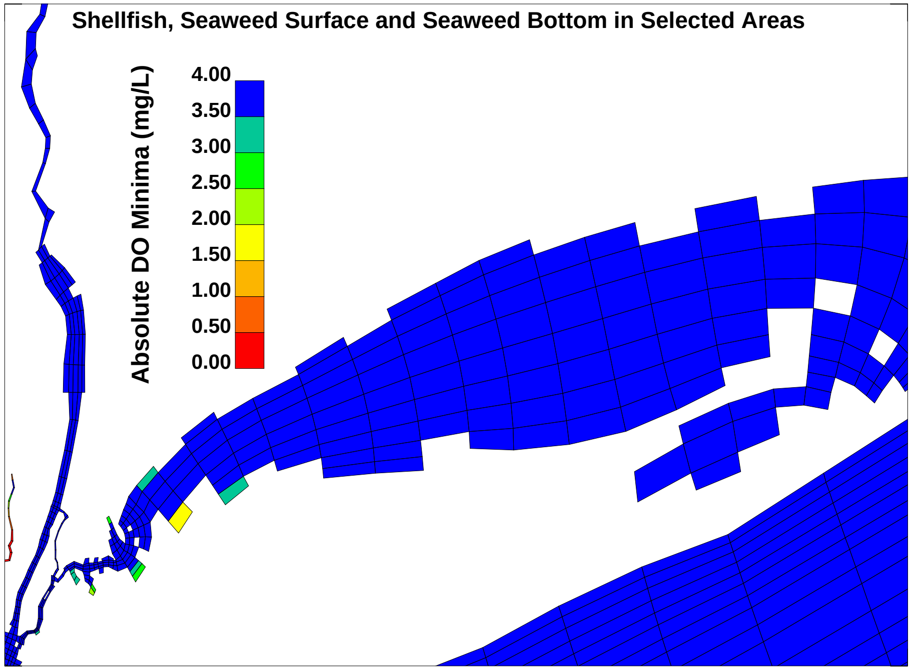


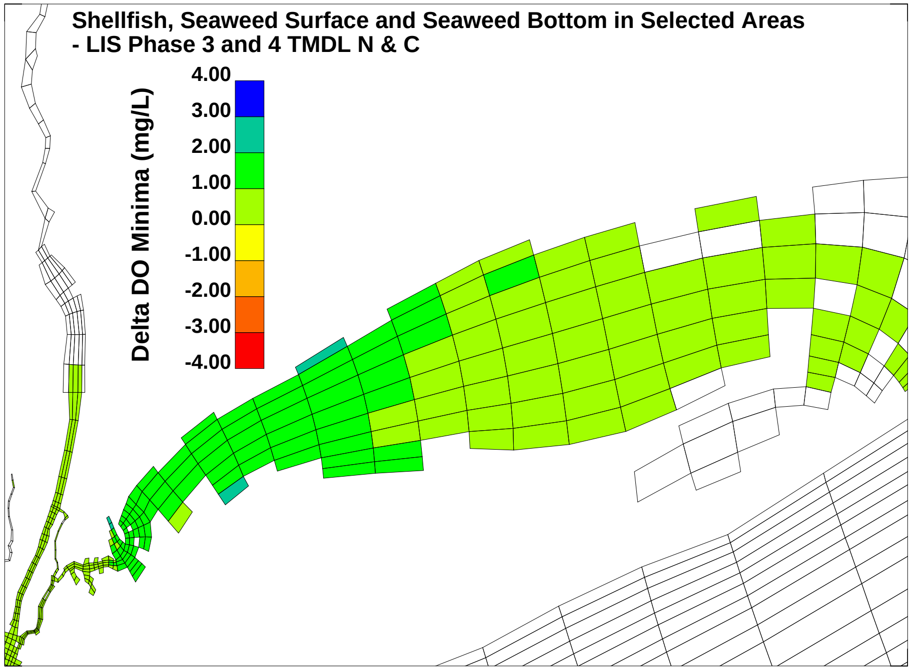




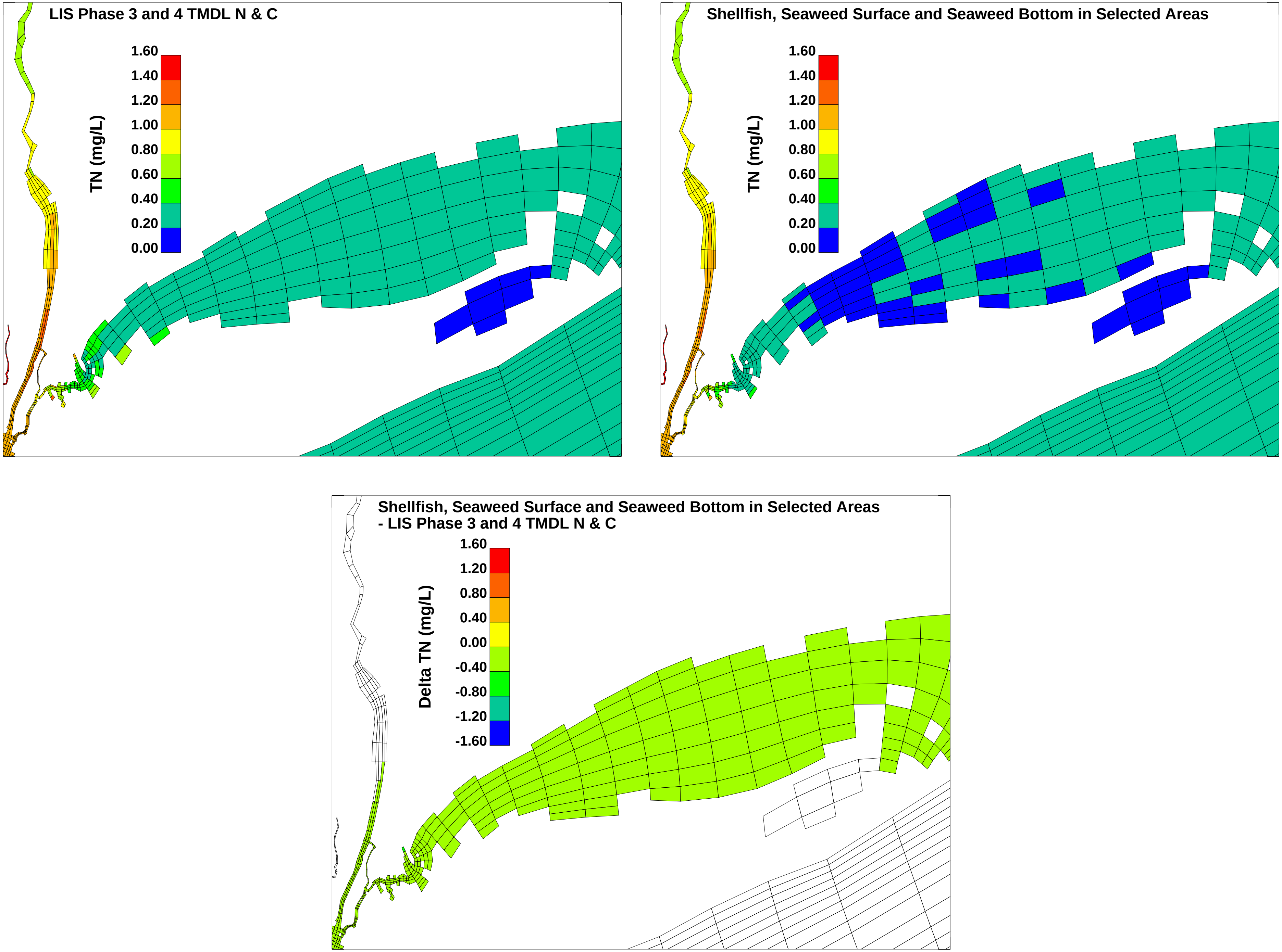
Absolute DO Minima, 1988 Hydrodynamic Conditions


LIS Phase 3 and 4 TMDL N & C

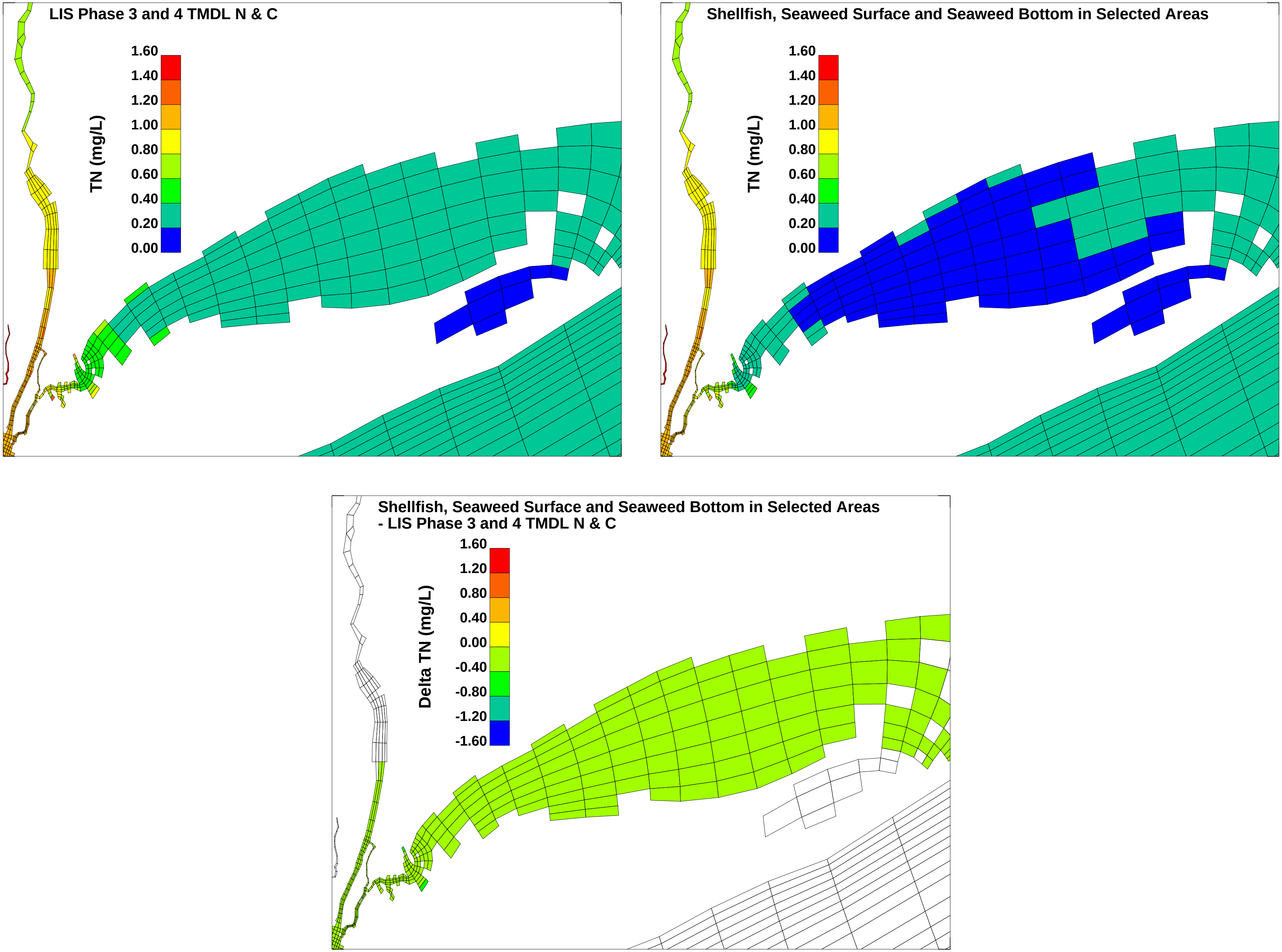

Shellfish, Seaweed Surface and Seaweed Bottom in Selected Areas


Shellfish, Seaweed Surface and Seaweed Bottom in Selected Areas
- LIS Phase 3 and 4 TMDL N & C

Absolute DO Minima, 1989 Hydrodynamic Conditions

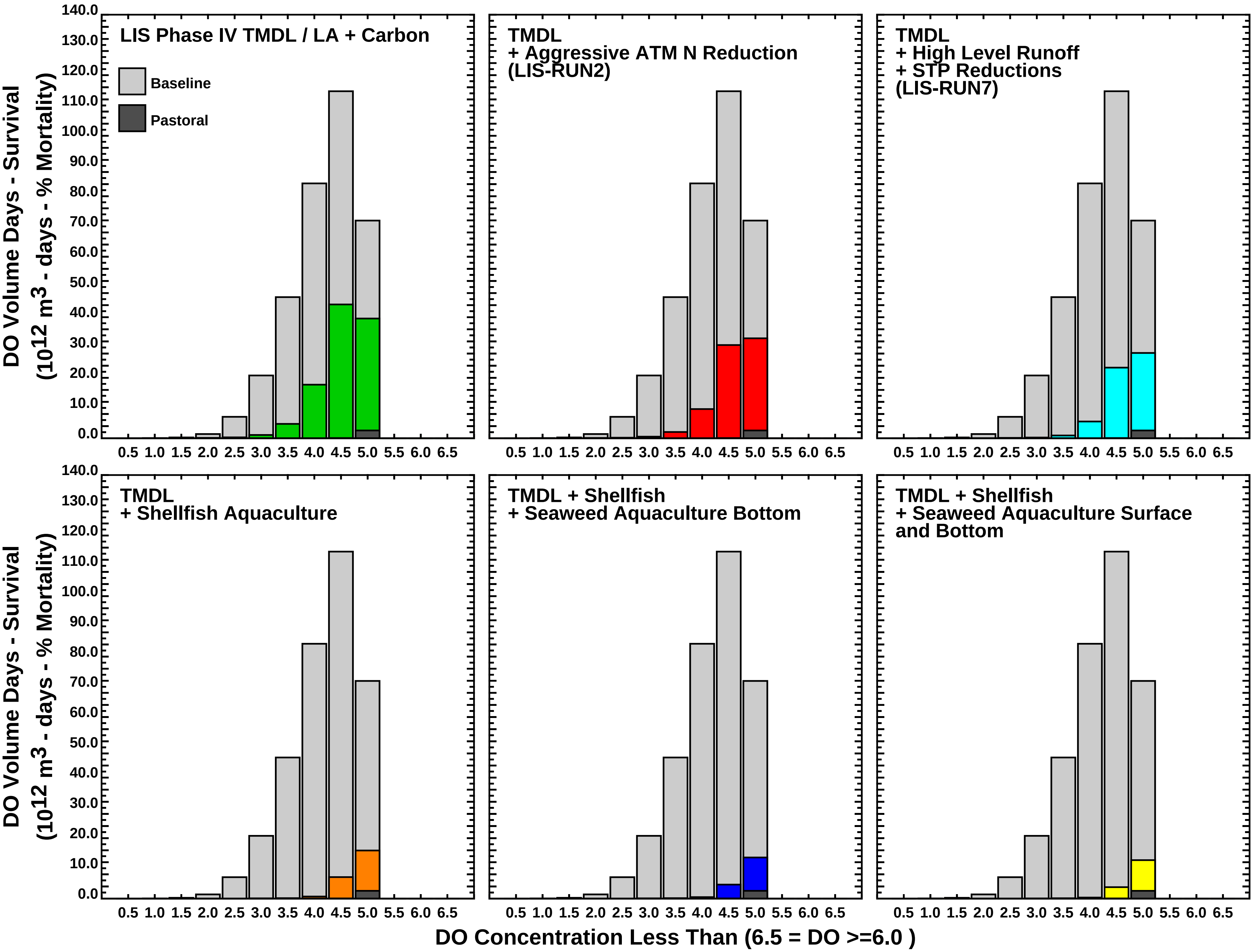


Total Nitrogen Corresponding to Absolute DO Minima, 1988 Hydrodynamic Conditions

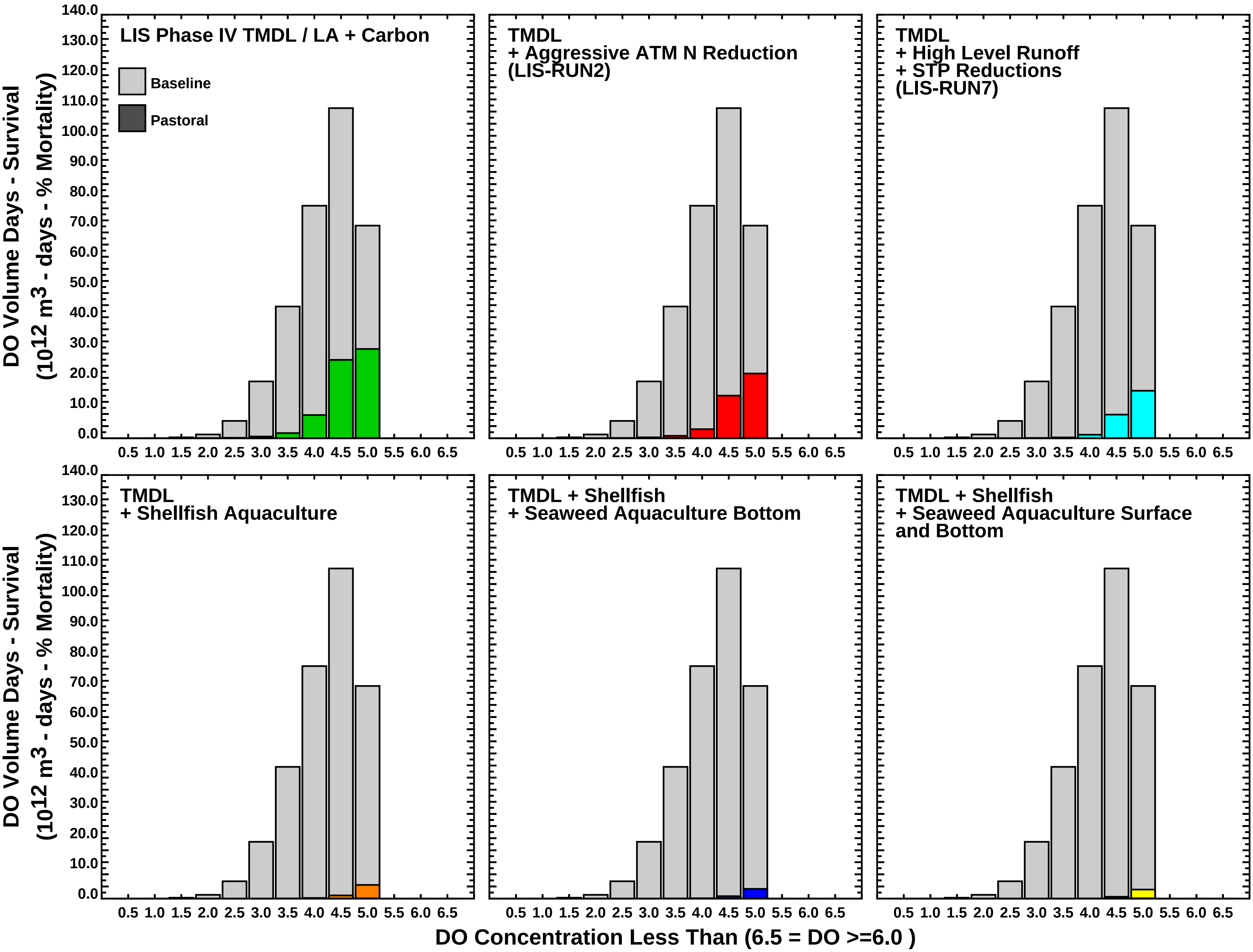


Total Nitrogen Corresponding to Absolute DO Minima, 1989 Hydrodynamic Conditions

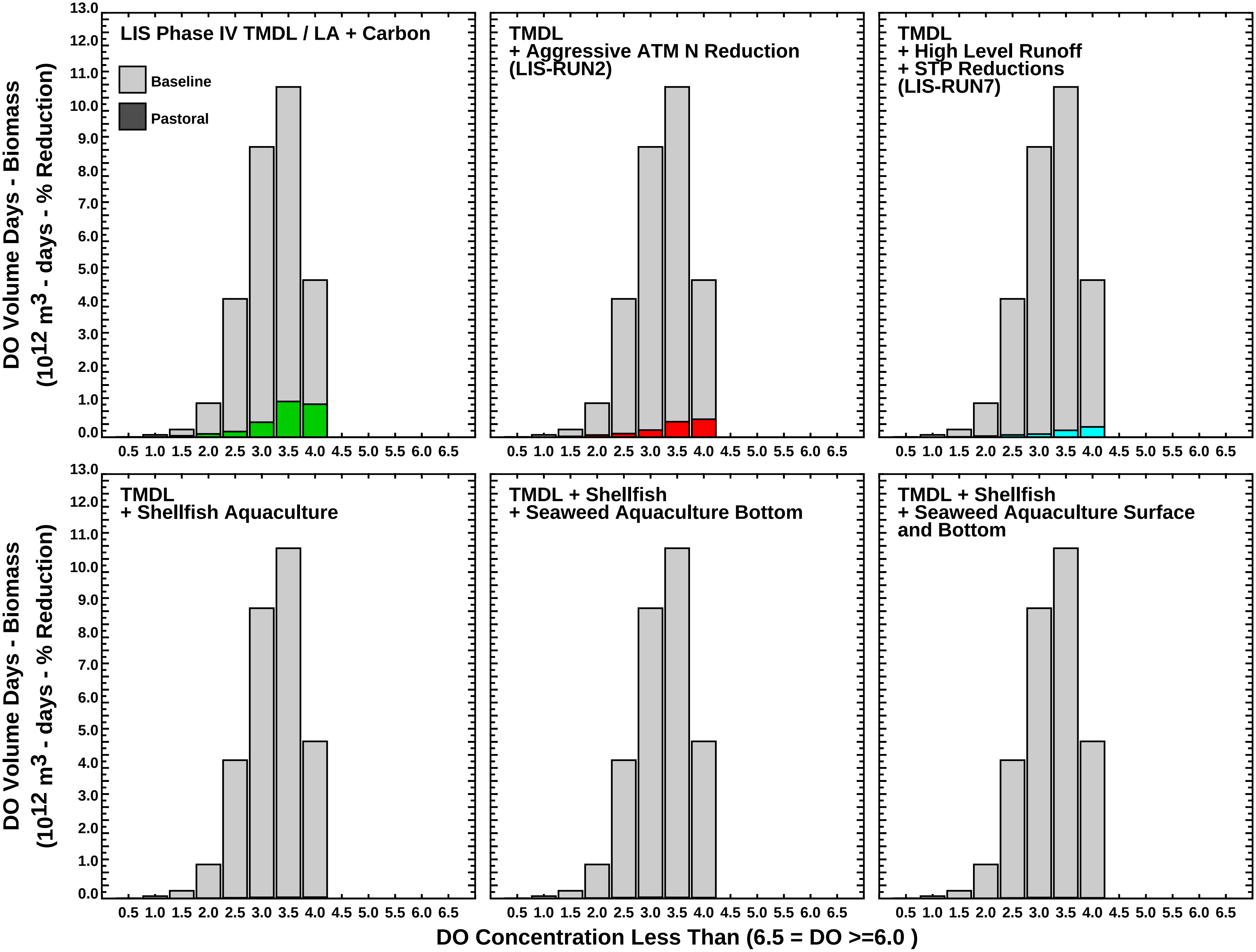
APPENDIX B
DISPLAYS OF LIVING MARINE RESOURCES METRICS



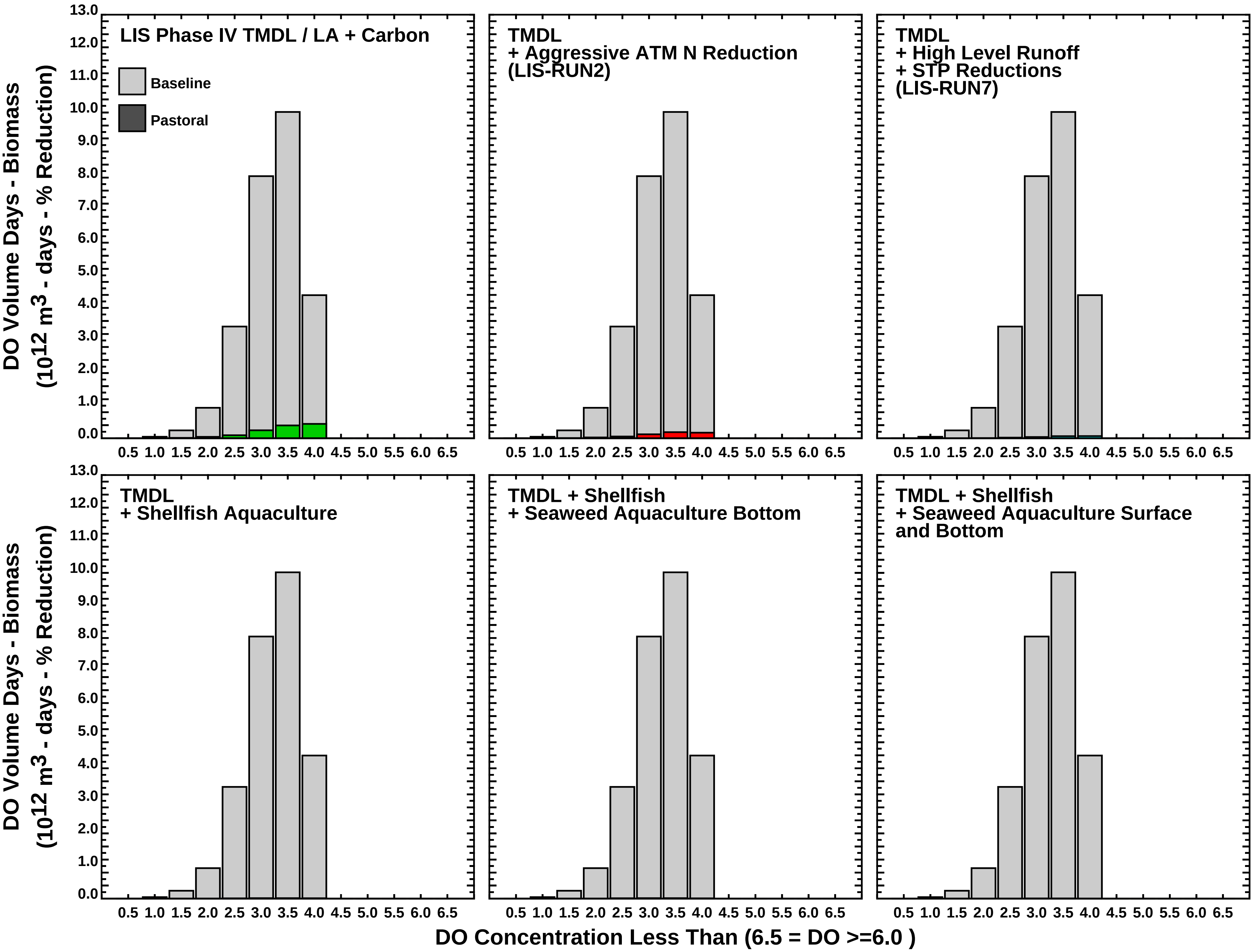
Total LIS DO Volume Days - Survival For 1988 Hydrodynamic Conditions



Total LIS DO Volume Days - Survival For 1989 Hydrodynamic Conditions

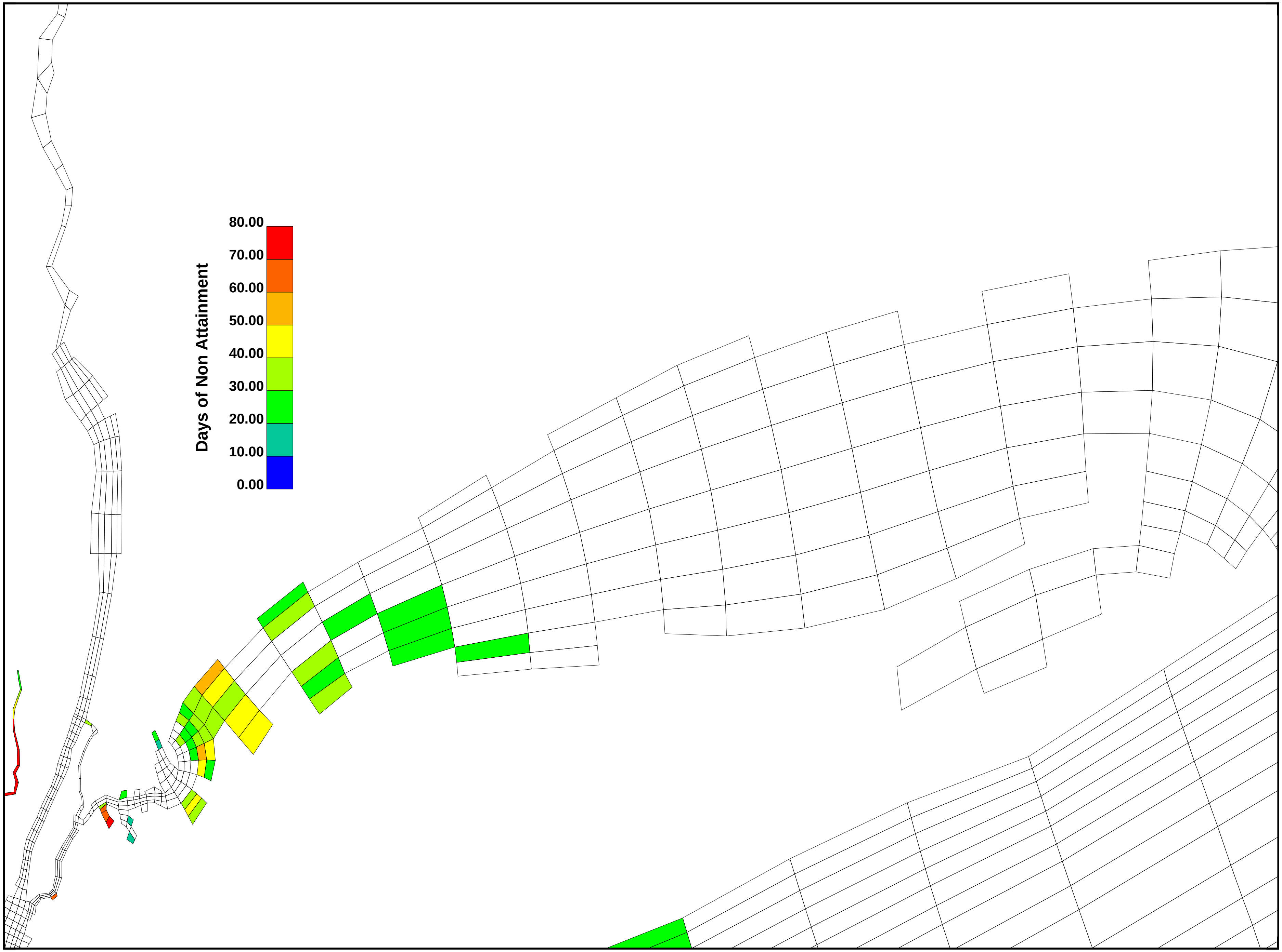


Total LIS DO Volume Days - Biomass For 1988 Hydrodynamic Conditions



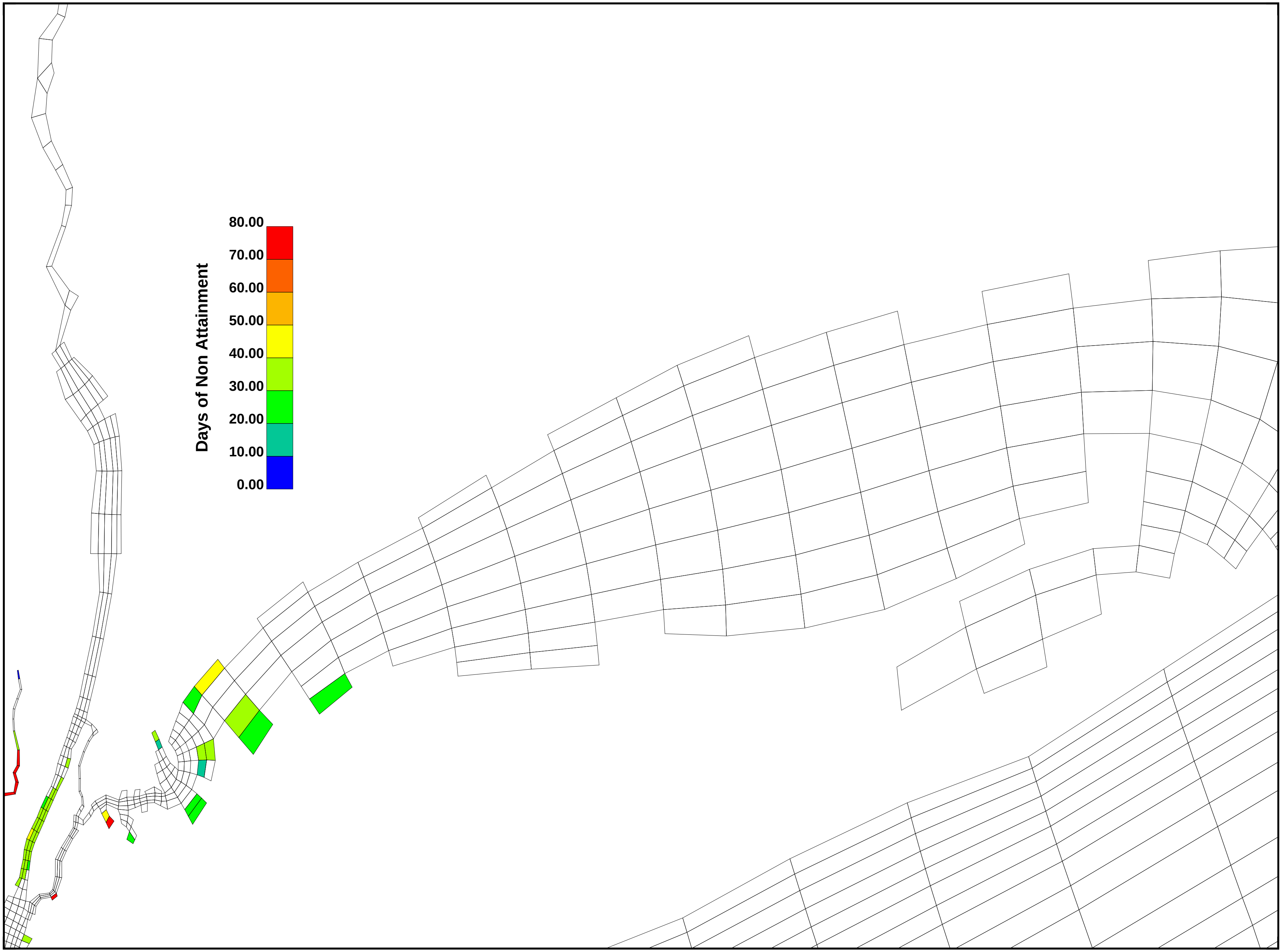
Total LIS DO Volume Days - Biomass For 1989 Hydrodynamic Conditions

APPENDIX C
DAYS OF STANDARDS ATTAINMENT MAPS
NY STANDARDS
(Phase IV TMDL + Carbon Loadings with Shellfish and Seaweed Extraction Cases)



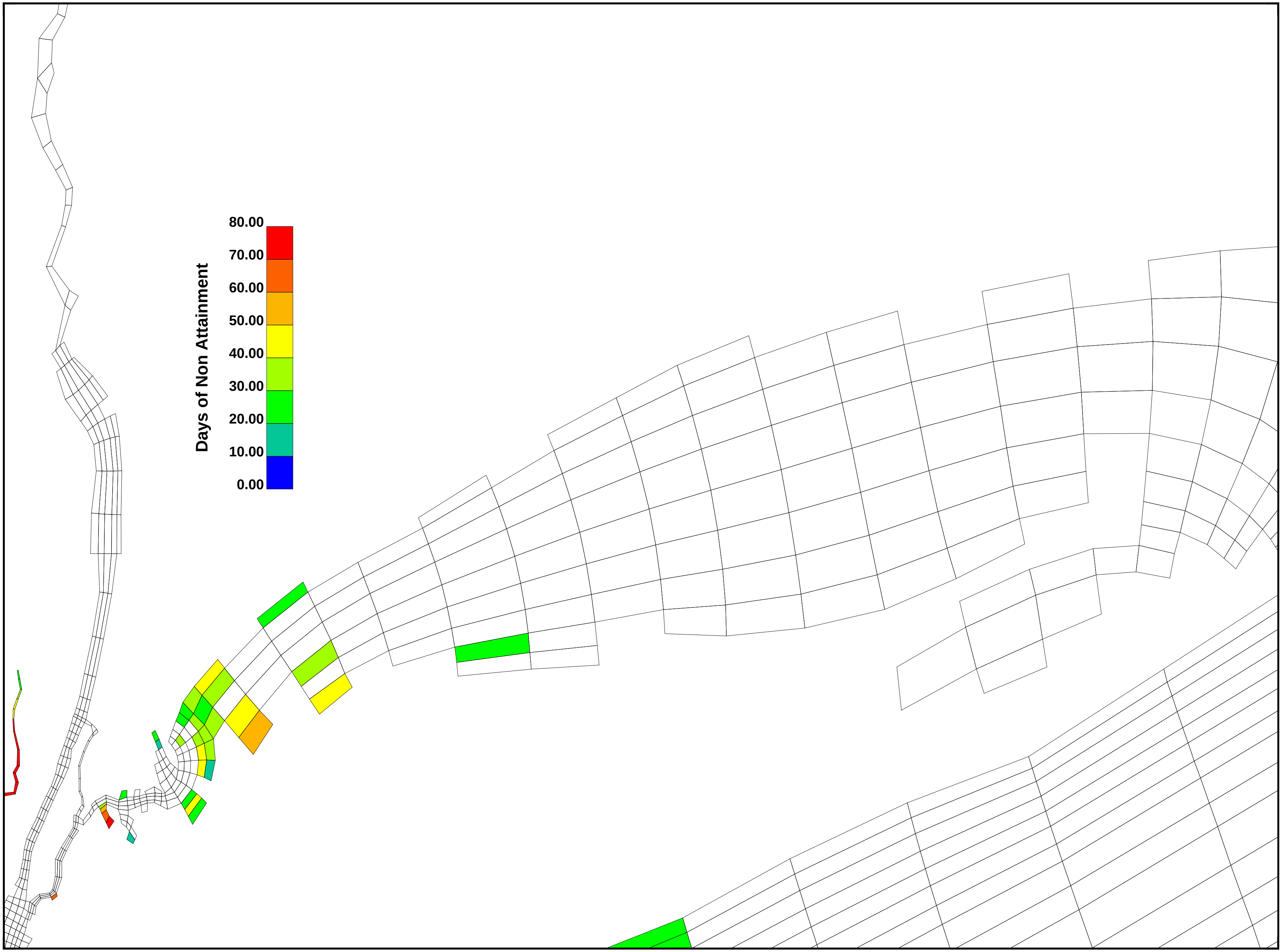
New York State Chronic Criteria

Shellfish 75% Assimilation, Approved areas less than 50ft Adj., 1988 Hydrodynamic Conditions



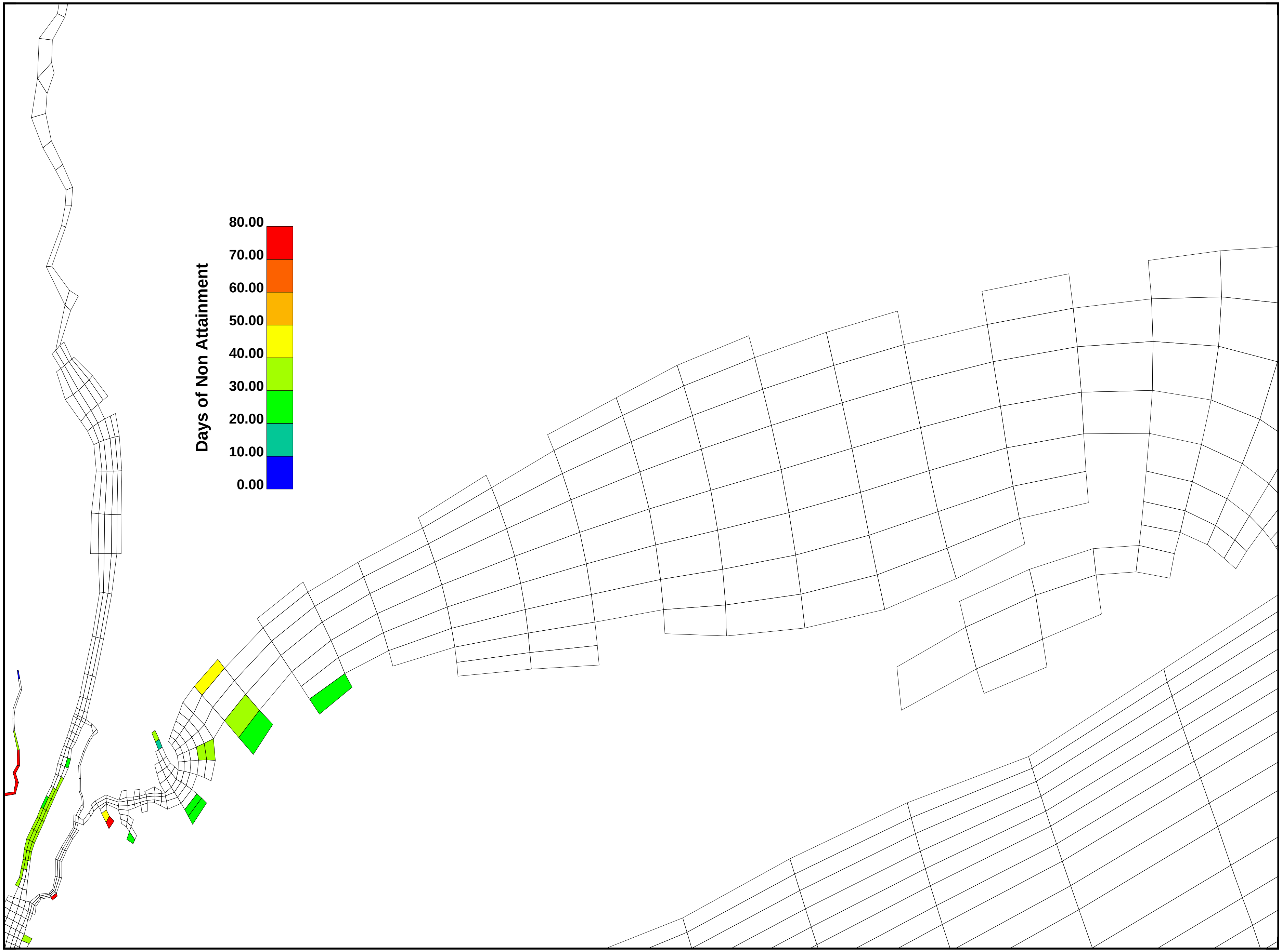
New York State Chronic Criteria

Shellfish 75% Assimilation, Approved areas less than 50ft Adj., 1989 Hydrodynamic Conditions



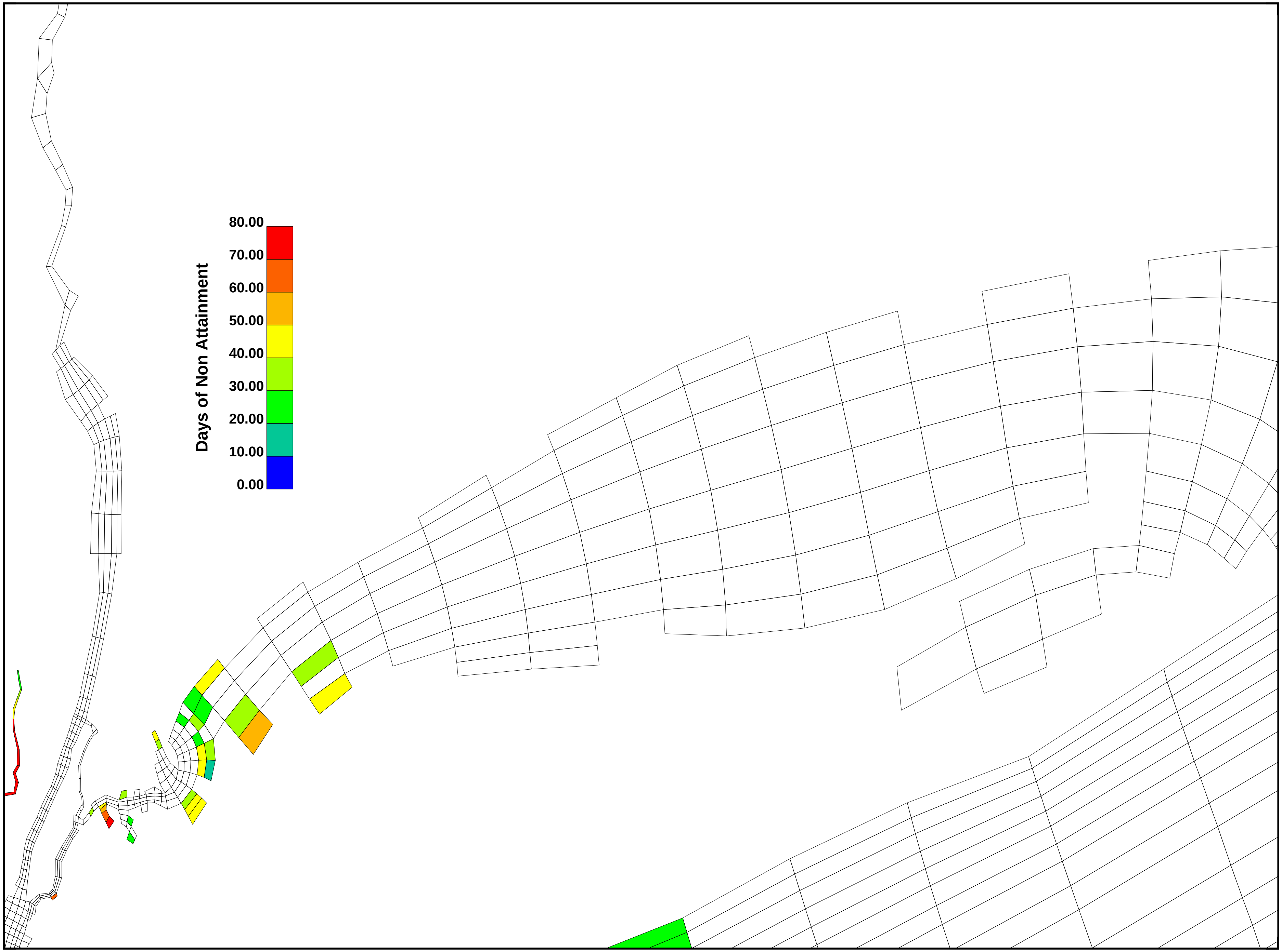
New York State Chronic Criteria

Shellfish Approved < 50ft Adj., Seaweed Bottom < 50ft with light, 1988 Hydrodynamic Conditions



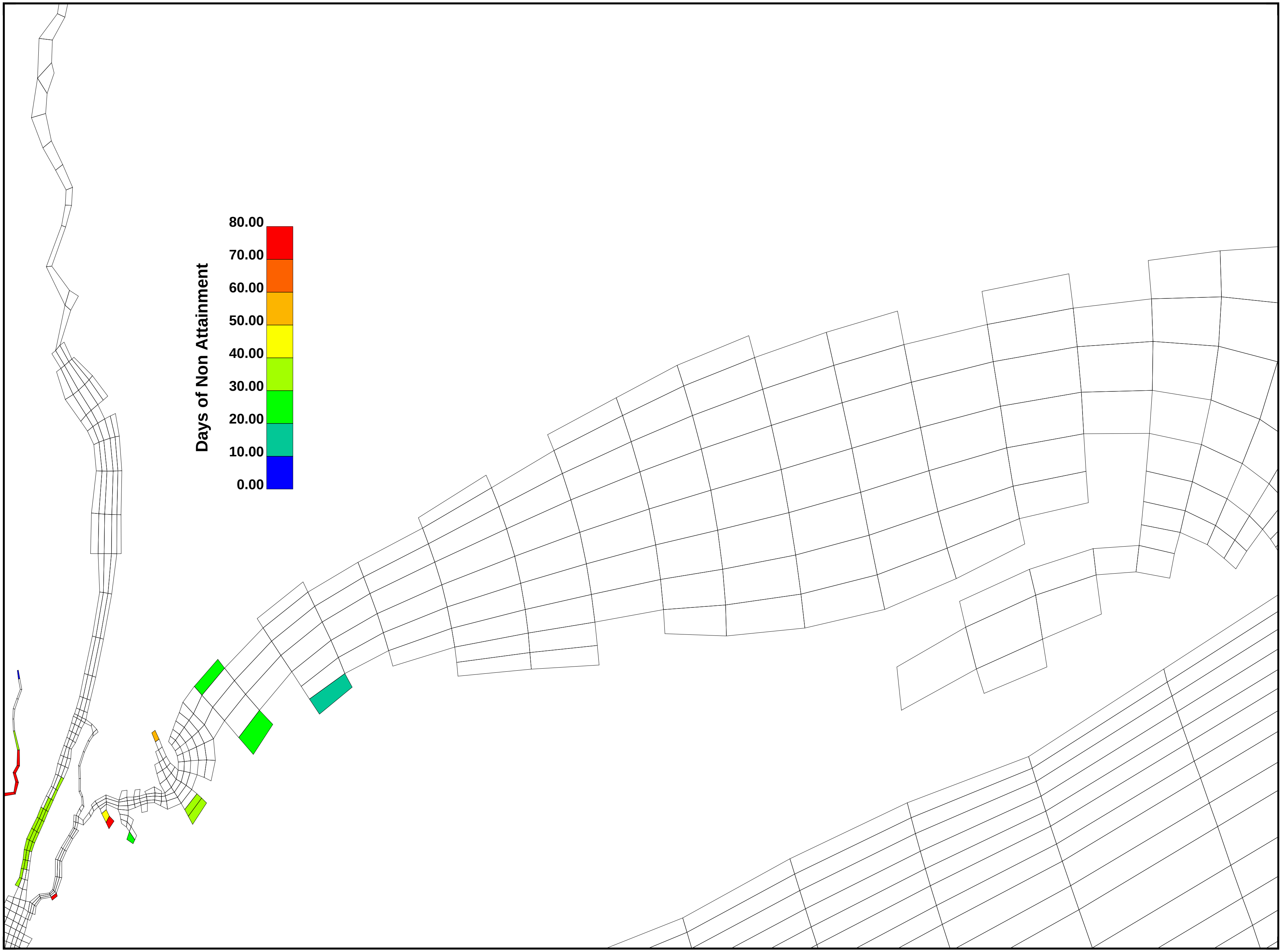
New York State Chronic Criteria

Shellfish Approved < 50ft Adj., Seaweed Bottom < 50ft with light, 1989 Hydrodynamic Conditions



New York State Chronic Criteria

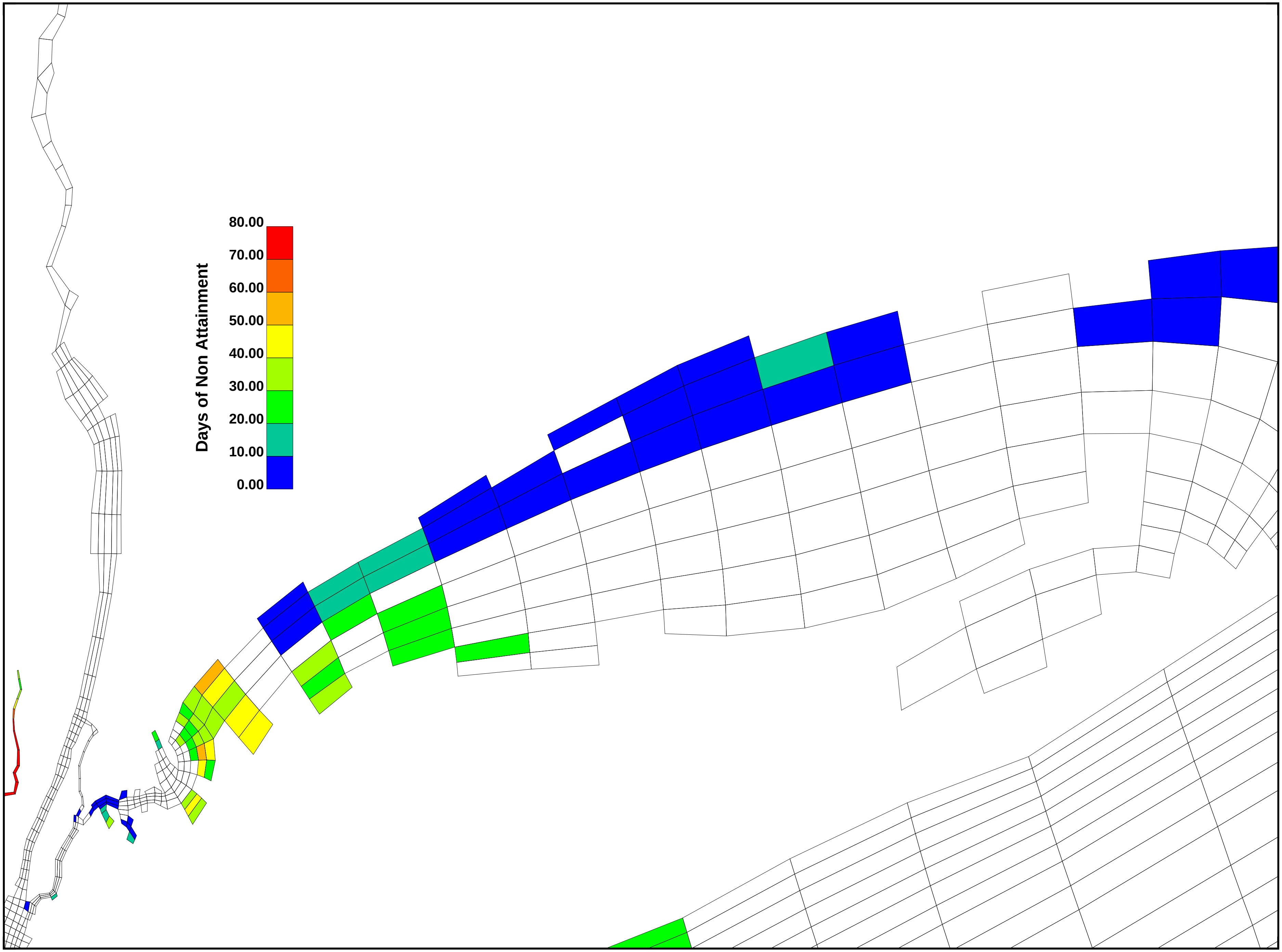
Shellfish, Seaweed Surface and Seaweed Bottom in Selected Areas, 1988 Hydrodynamic Conditions



New York State Chronic Criteria

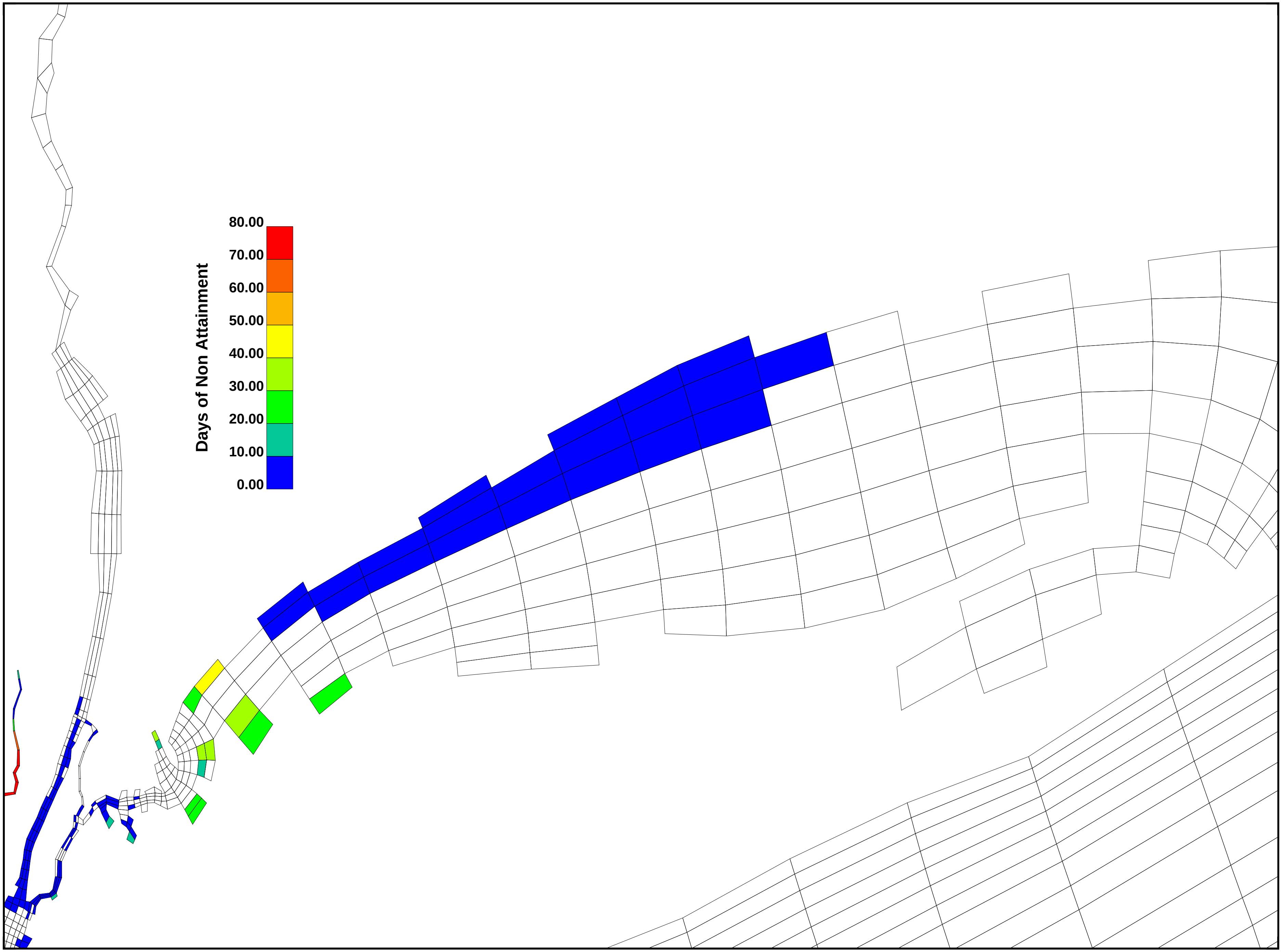
Shellfish, Seaweed Surface and Seaweed Bottom in Selected Areas, 1989 Hydrodynamic Conditions

APPENDIX D
DAYS OF STANDARDS ATTAINMENT MAPS
CURRENT NY & CT STANDARDS
(Phase IV TMDL + Carbon Loadings with Shellfish and Seaweed Extraction Cases)



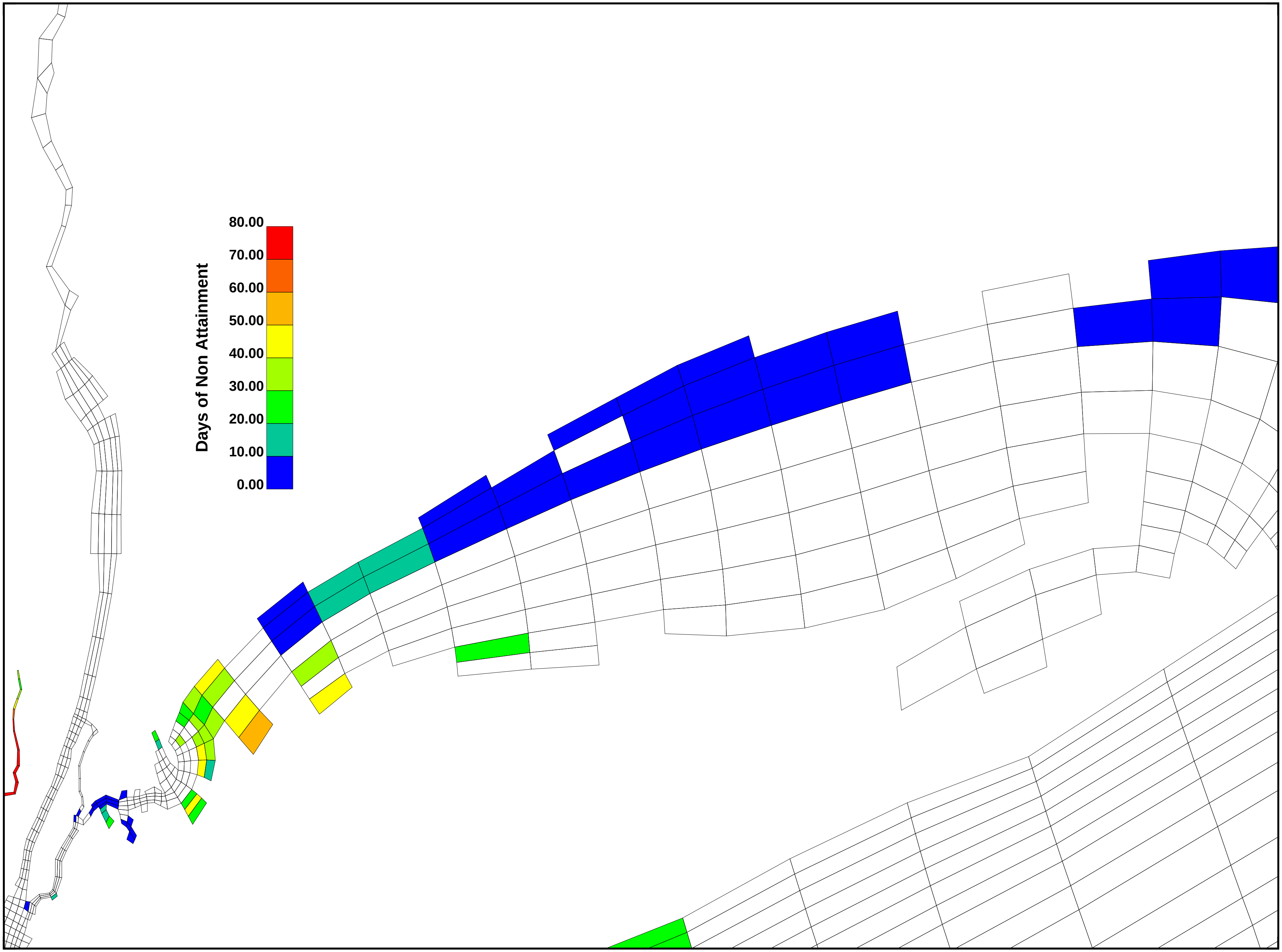
Current Dissolved Oxygen Standards - NYS Marine DO Criteria

Shellfish 75% Assimilation, Approved areas less than 50ft Adj., 1988 Hydrodynamic Conditions



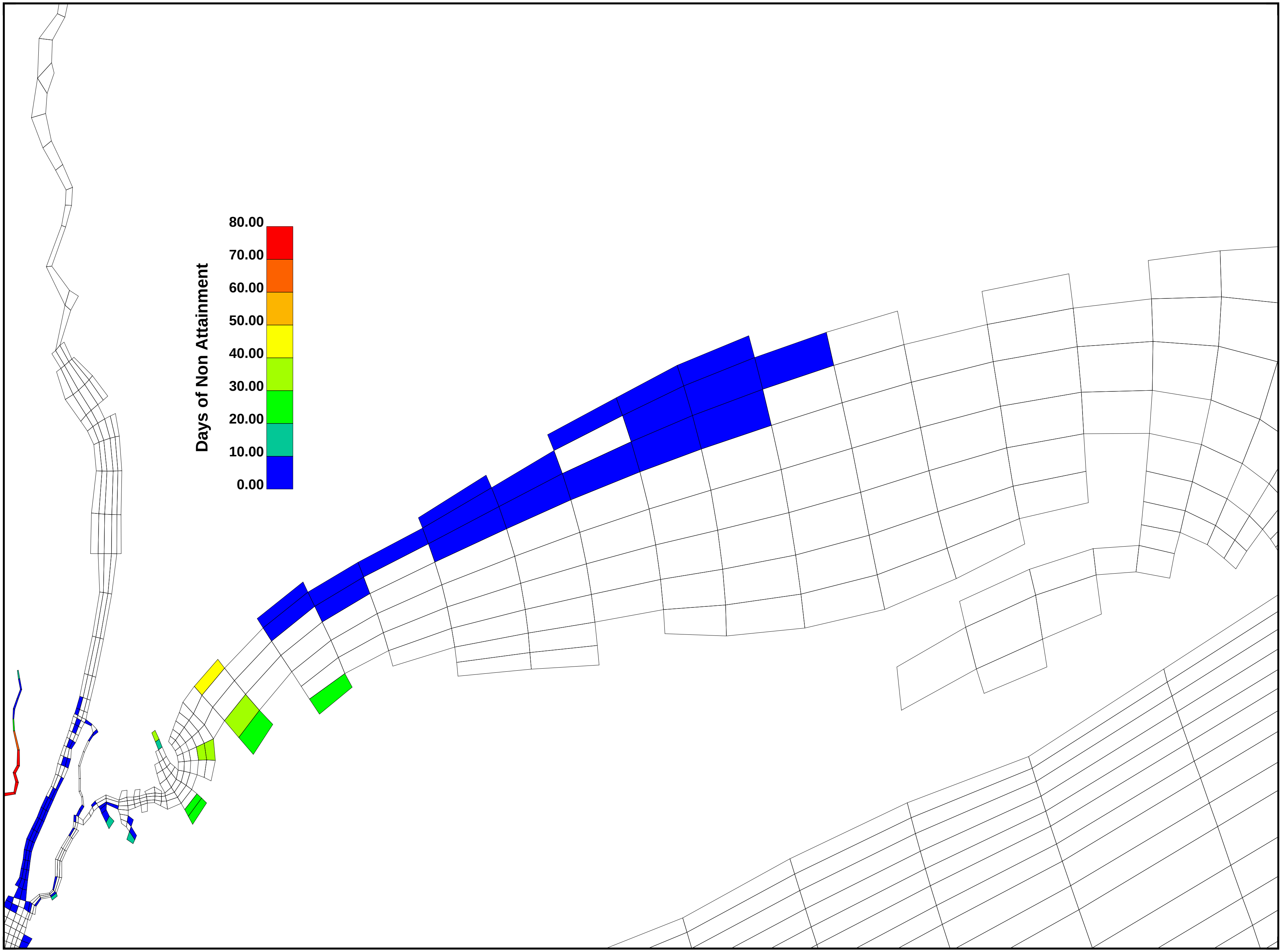
Current Dissolved Oxygen Standards - NYS Marine DO Criteria

Shellfish 75% Assimilation, Approved areas less than 50ft Adj., 1989 Hydrodynamic Conditions



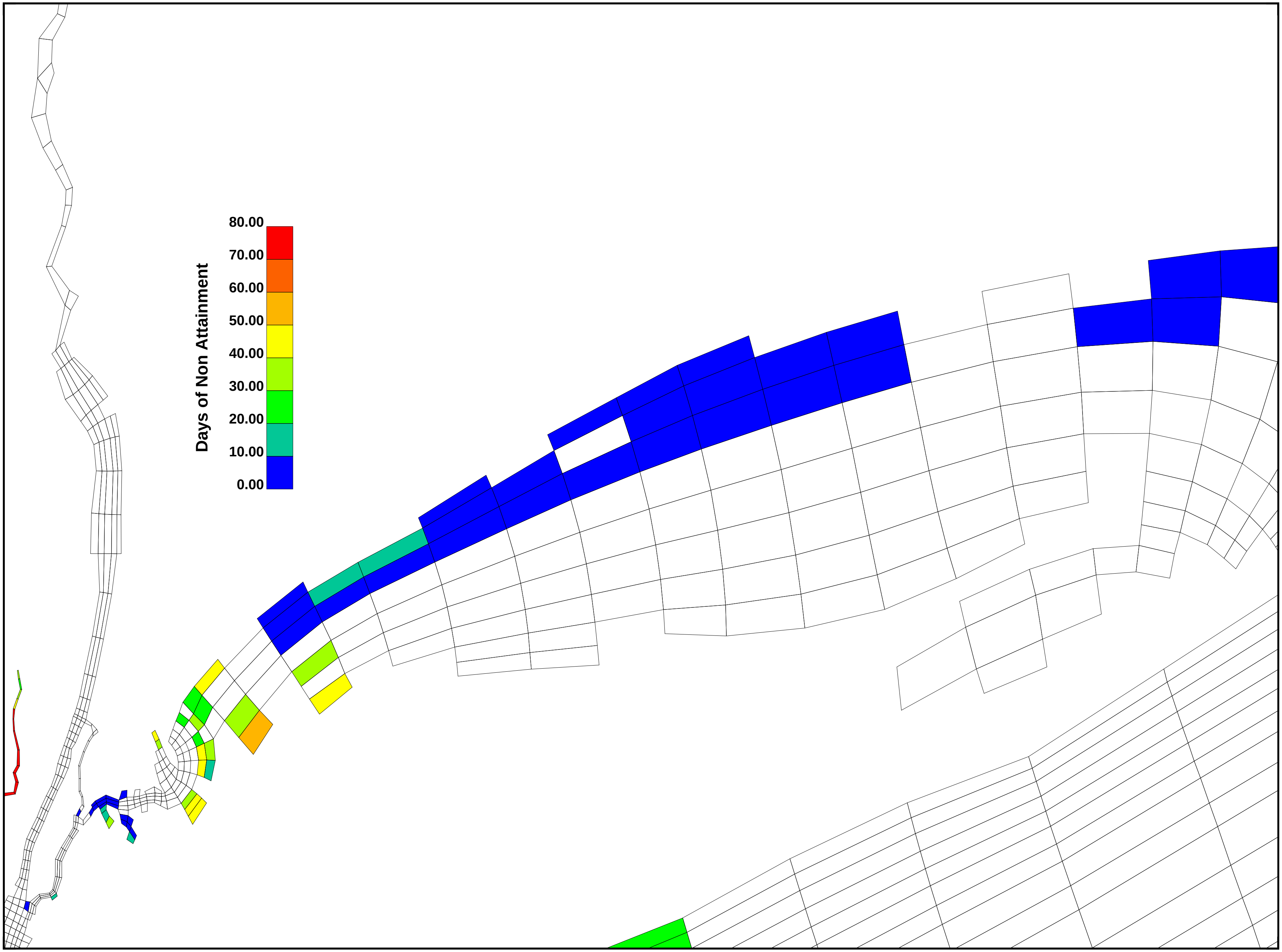
Current Dissolved Oxygen Standards - NYS Marine DO Criteria

Shellfish Approved < 50ft Adj., Seaweed Bottom < 50ft with light, 1988 Hydrodynamic Conditions



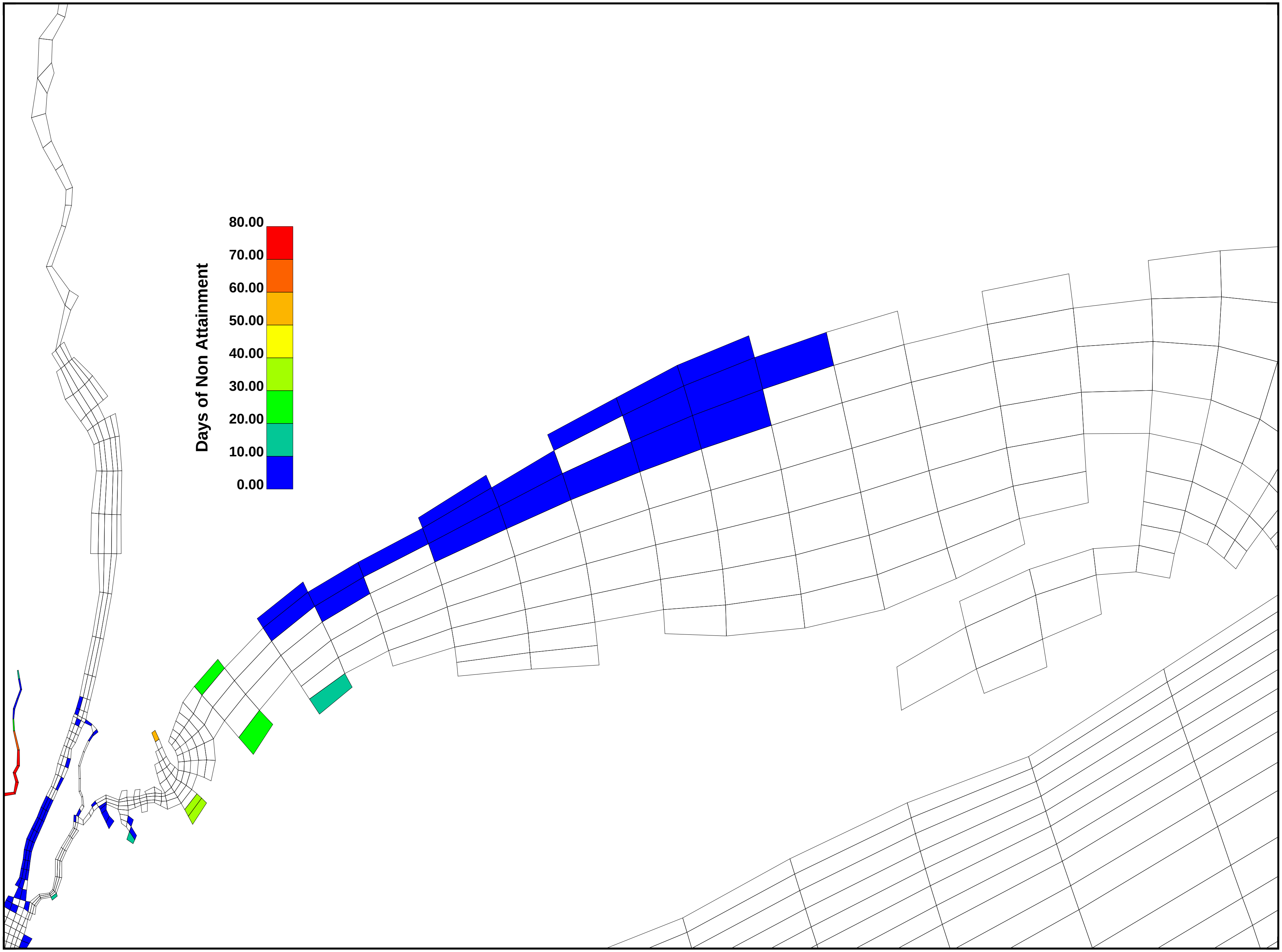
Current Dissolved Oxygen Standards - NYS Marine DO Criteria

Shellfish Approved < 50ft Adj., Seaweed Bottom < 50ft with light, 1989 Hydrodynamic Conditions



Current Dissolved Oxygen Standards - NYS Marine DO Criteria

Shellfish, Seaweed Surface and Seaweed Bottom in Selected Areas, 1988 Hydrodynamic Conditions



Current Dissolved Oxygen Standards - NYS Marine DO Criteria

Shellfish, Seaweed Surface and Seaweed Bottom in Selected Areas, 1989 Hydrodynamic Conditions