EVALUATION OF NITROGEN TARGETS AND WWTF LOAD REDUCTIONS FOR THE PROVIDENCE AND SEEKONK RIVERS

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DECEMBER 2004

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APPROACHES FOR ESTABLISHING A NITROGEN LOAD REDUCTION PLAN

The Providence and Seekonk Rivers are impacted by low dissolved oxygen levels and high phytoplankton concentrations that are related to excessive nitrogen loadings. DEM has collected data and has been working with a contractor to develop a water quality model and a water quality restoration plan (Total Maximum Daily Load (TMDL)) for the area. It has recently been determined that due to problems encountered when modeling the interaction between the deep channel and shallow flanks of these water bodies, the mass transport component of the model system cannot be successfully calibrated and validated. This problem has been encountered in other estuaries and has not been resolved with state of the art numerical solution techniques. Because water doesn't mix in the model as it does in the rivers, we are unable to simulate the chemical and biological behavior of the system in the water quality phase of the modeling effort.

Our inability to adequately validate the mass transport model also prevents us from applying the Massachusetts approach to setting load allocations that uses ambient total nitrogen concentration as the indicator, which is described below. Other elements of the Massachusetts approach were found to be helpful in the goal-setting phase of this discussion, however.

When functioning properly, a water quality model predicts an accurate water quality condition that results from a set of inputs (pollutant loadings) to the system. A computer-based numerical model is typically used, however a physical model can also serve as the analog for the river. In this case, information is available from the MERL (Marine Ecosystems Research Laboratory) enrichment gradient experiment (Oviatt et al, 1986). DEM had initially used relationships observed during the MERL experiment to establish kinetic terms in the numerical model, however the experimental results themselves can also be used.

THE MERL EXPERIMENT AND BEHAVIOR OF KEY PROCESSES

The enrichment gradient experiment was conducted continuously between May 1981 and September 1983. A complete set of environmental variables and water column parameters were measured throughout the period of the study. These included weekly sampling of chlorophyll-a, DIN, DO from consecutive dawn-dusk-dawn measurements, daily production, and monthly benthic uptake.

The experiment was conducted in nine 13,000 L tanks at URI. Three control tanks, consisting of lower Bay water with no enrichment comprised the first group. The next group consisted of the low treatments: 1X, 2X, and 4X tanks, where the 1x addition rate represented the mean addition rate (per unit area) of inorganic nitrogen, phosphorus, and silicon to Narragansett Bay. The final group consisted of the high treatments: 8X, 16X, and 32X additions, where the 8X case was considered representative of the Providence River, and the 32X case represented the Hudson River region of New York Harbor. In general, the 1X- 32X loading gradient was selected to reproduce the range of enrichment levels seen in real estuaries. The loading gradients and corresponding DIN loading rates are listed in Table 1.

Table 1. MERL Loading Gradients and DIN Loading Rates

Loading Gradient	DIN Loading Rate	
	mmole/m2/day	kg/m2/day
1	2.88	4.032E-05
2	5.76	8.064E-05
4	11.52	1.613E-04
8	23.04	3.226E-04
16	46.08	6.451E-04
32	92.16	1.290E-03

As an initial phase of her project to refine the WASP kinetics for DEM, Dr. Aimee Keller evaluated the MERL results to extract information that would be used in the proposed application of the WASP model for the Providence River. From the mesocosm data, Dr. Keller documented a number of characteristics of the MERL tanks that have significance for the Providence and Seekonk Rivers:

Dissolved oxygen:
The DO observations for the three groups of tanks are shown below.

- The most significant features of DO behavior are that as the nutrient addition level increases, DO minimum levels drop precipitously and the variability increases. Figures 1, 2, and 3 summarize DO for the control tanks (mouth of bay water with no nutrient addition), low treatments (1X, 2X, and 4X) and high treatments (8X, 16X, and 32X), respectively. The three figures show a distinct increase in deviation from the saturation concentration shown by the solid red line in each figure with increasing addition rate.
- Another significant feature is an exponential drop in minimum summer values with increasing nutrient loadings (Figure 4). Summer minimum values for the three highest enrichments are less than 2 mg/l.
- The mean of observed DO concentrations also increases somewhat with increasing loading. (Figure 5). Seasonal maximum values also increase.
- Temperature appears to be the principal factor that affects DO at lower loading rates (Figure 6). At higher loadings, DO correlates significantly with ambient silica and nitrate concentrations.

Figure 4 is probably the most telling graphic of this group. Daily minimum DO values drop precipitously, to less than 2 mg/l, at the 8X, 16X, and 32X tanks. The regression equation derived from the tank data predicts DO minima of 3.7 mg/l, 3.0 mg/l, and 1.98 mg/l for the 2X, 4X, and 8X cases, respectively.

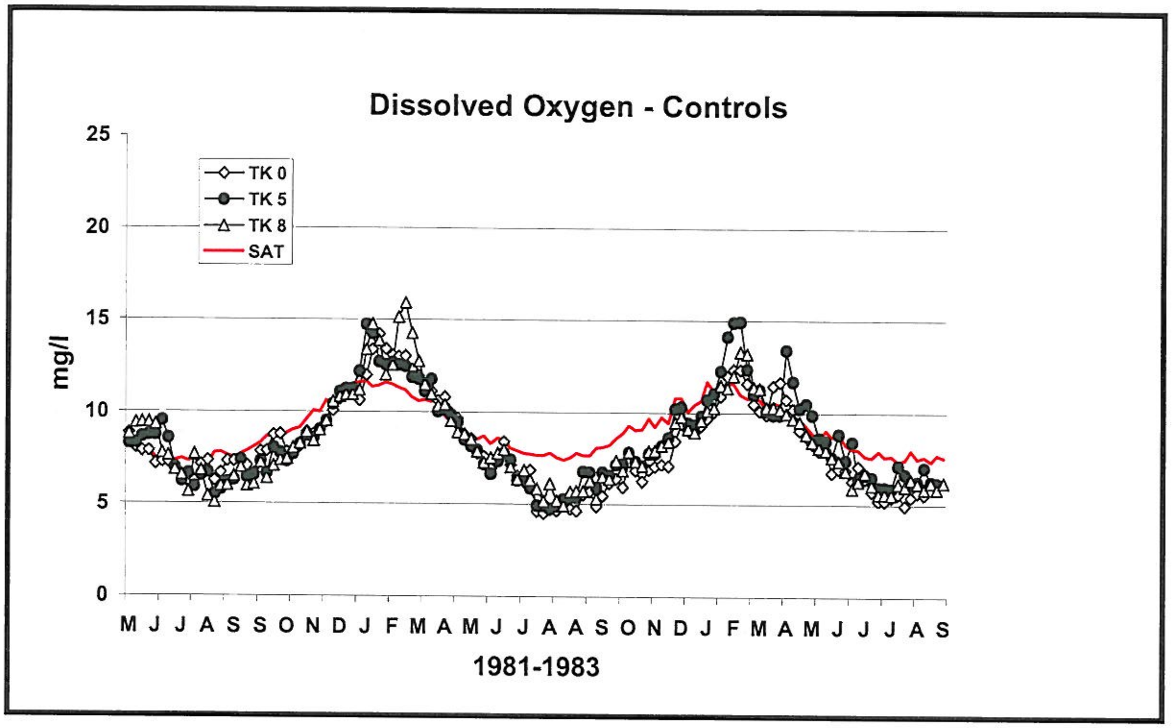

Figure 1: DO for the control tanks, May 1981 – September 1983.

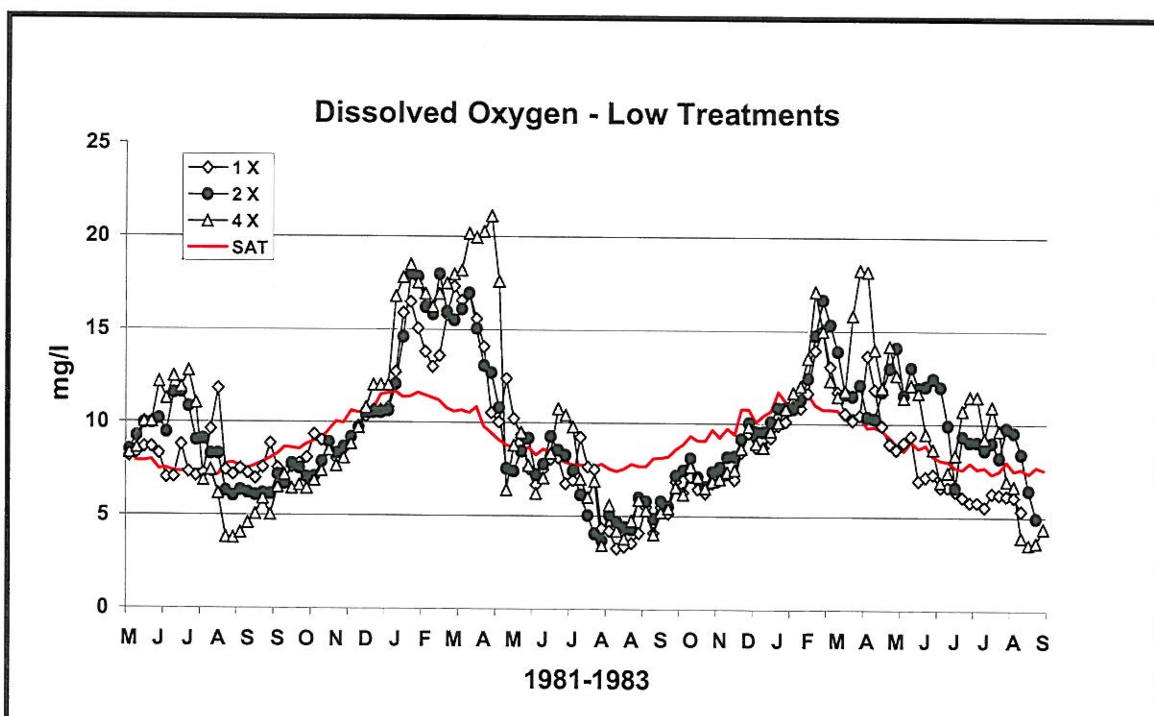

Figure 2: DO for the low level treatment tanks, May 1981 – September 1983.

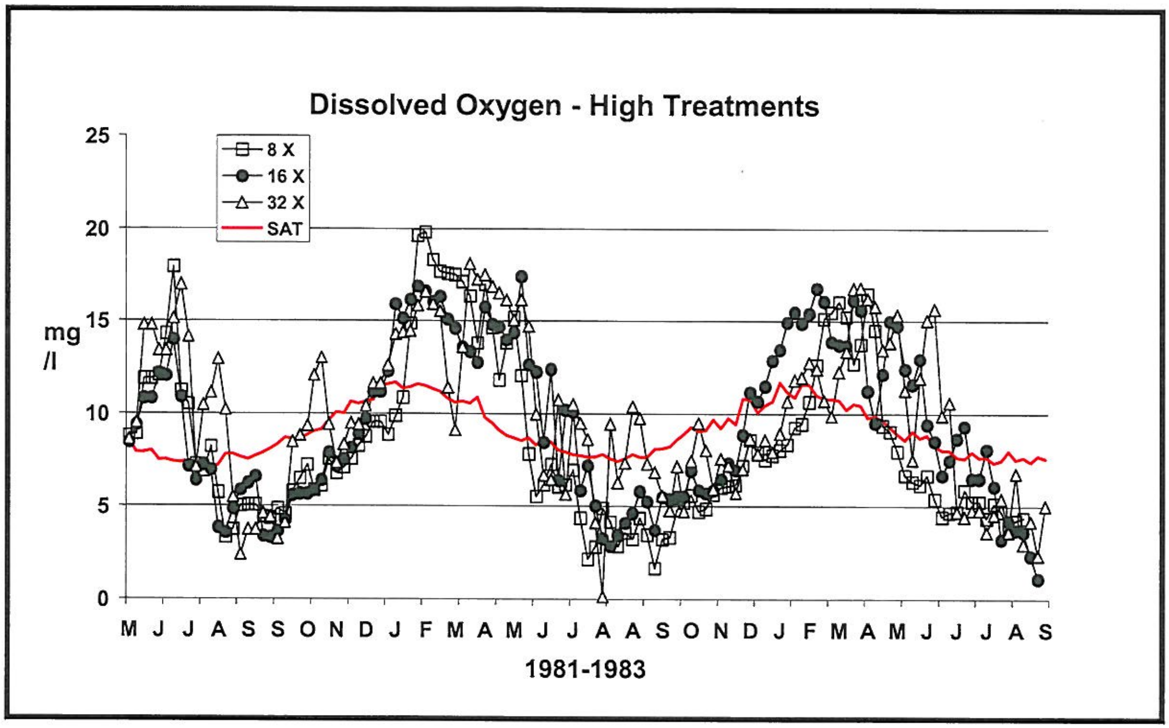

Figure 3: DO for the high level treatment tanks, May 1981 – September 1983.

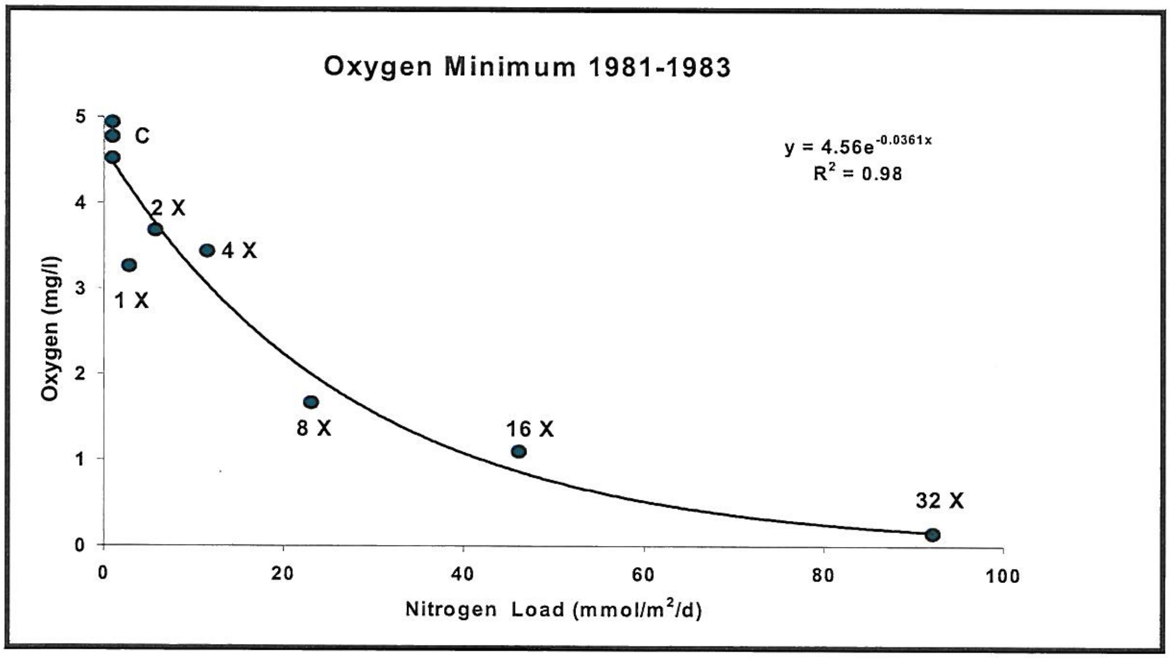

Figure 4: The relationship between the inorganic nitrogen loading rate and minimum observed oxygen concentration, which shows that the oxygen minimum drops rapidly with increasing loadings.

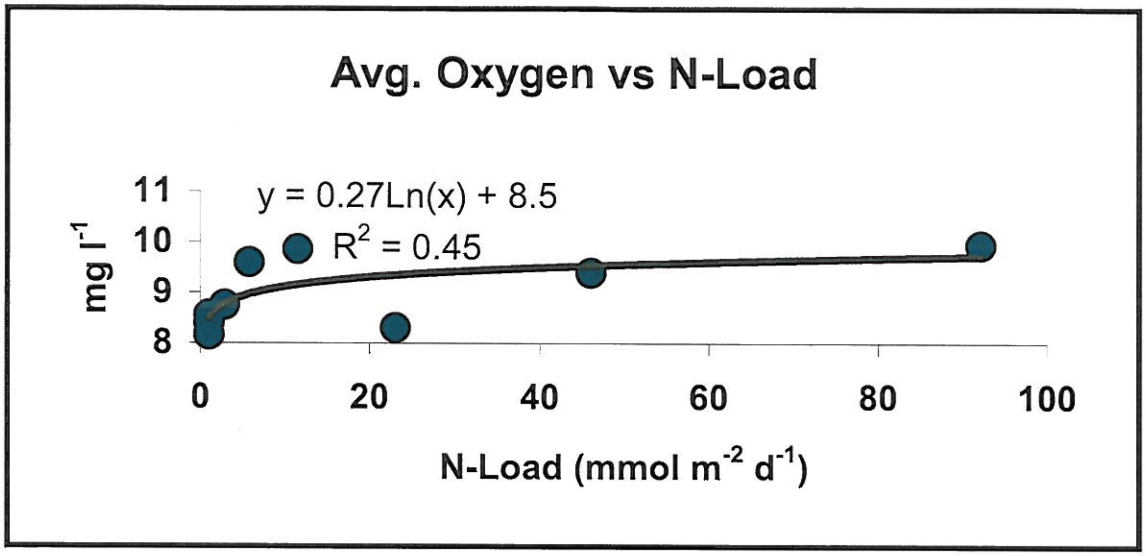

Figure 5: Graph of mean MERL tank DO as a function of loading, showing that the average DO goes up slightly as nutrient loadings are increased.

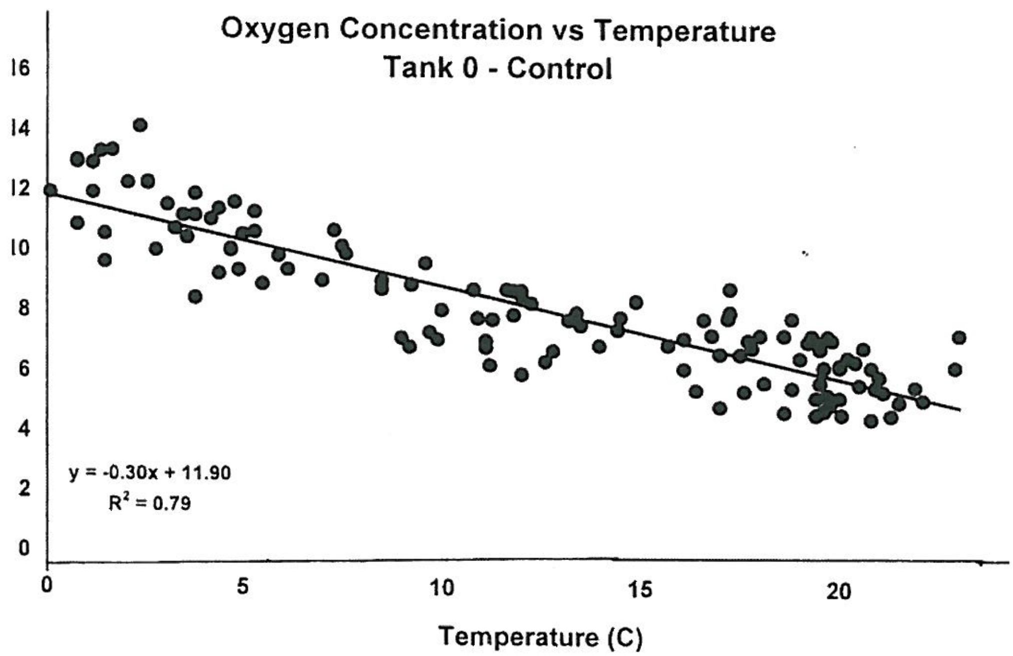

Figure 6: The relationship between DO and temperature in a control tank.

Phytoplankton:

- Figures 7 – 9 show observed chlorophyll levels in the three sets of tanks during the experiment. As with DO, the variability as well as the mean levels of chlorophyll increase as nutrient addition levels are increased.
- The 4X and above treatments experience peak chlorophyll levels of 100 ug/l or greater.
- The variability of chlorophyll in the 8X and higher tanks could best be described as chaotic (Figure 9). Adjacent weekly measurements in these tanks appear to have swung from one extreme to another on a weekly basis. The 8X is somewhat disparate because the tank was inadvertently colonized by a disparately high number of filter feeders that unrealistically depressed both the variations and the mean levels of phytoplankton. This result indicates that filter feeders can mitigate the effects of increased nutrient loadings by reducing phytoplankton blooms, however filter feeders exert an oxygen demand through their respiration that may exacerbate hypoxia under some conditions.
- The mean level of phytoplankton increases linearly with increasing nitrogen loading rate (Figure 10).

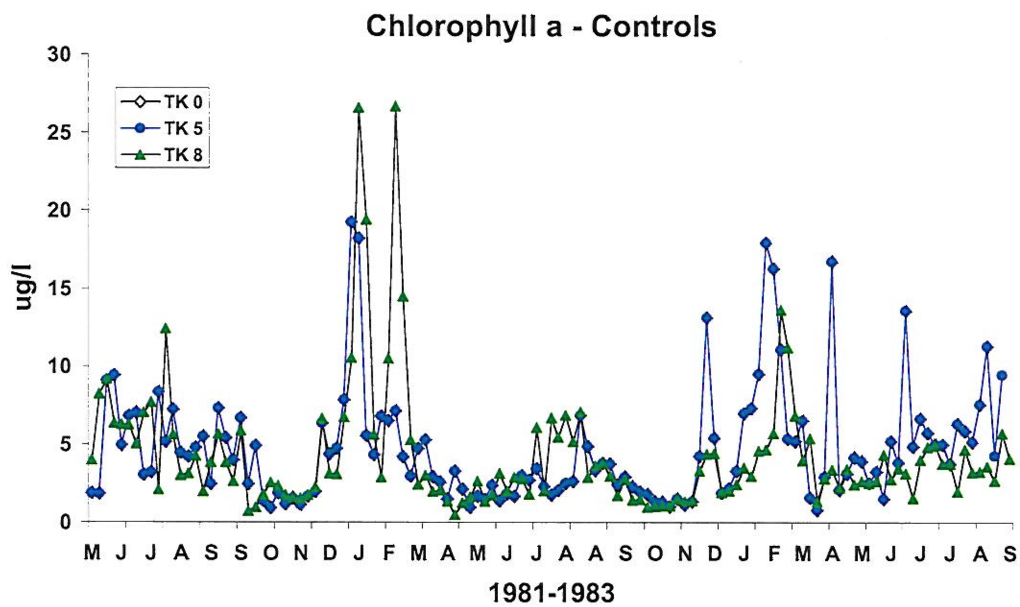

Figure 7: Phytoplankton biomass in the control tanks, May 1981 – September 1983.

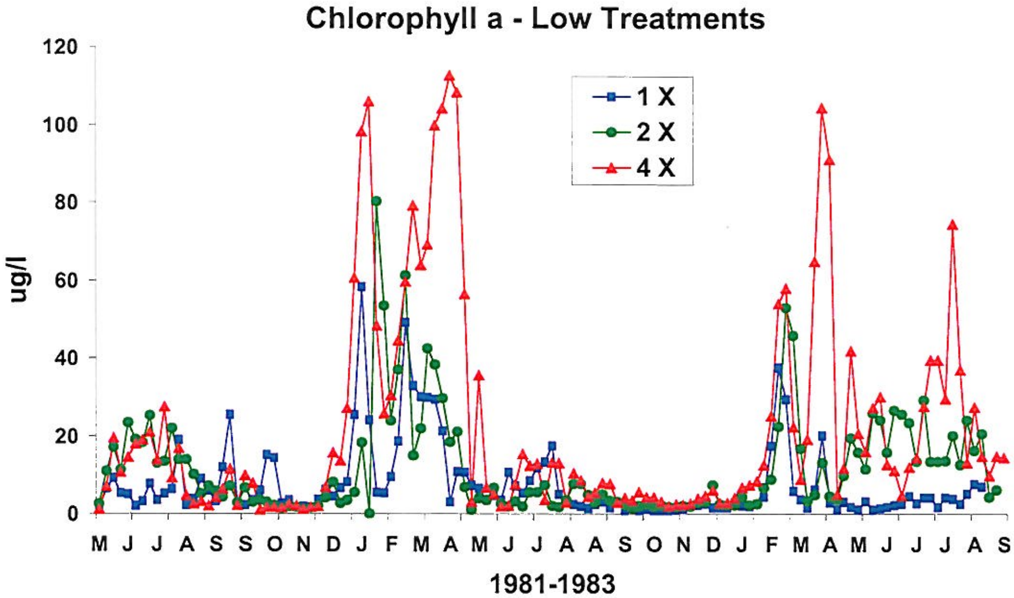

Figure 8: Phytoplankton biomass in the low treatment tanks, May 1981 – September 1983.

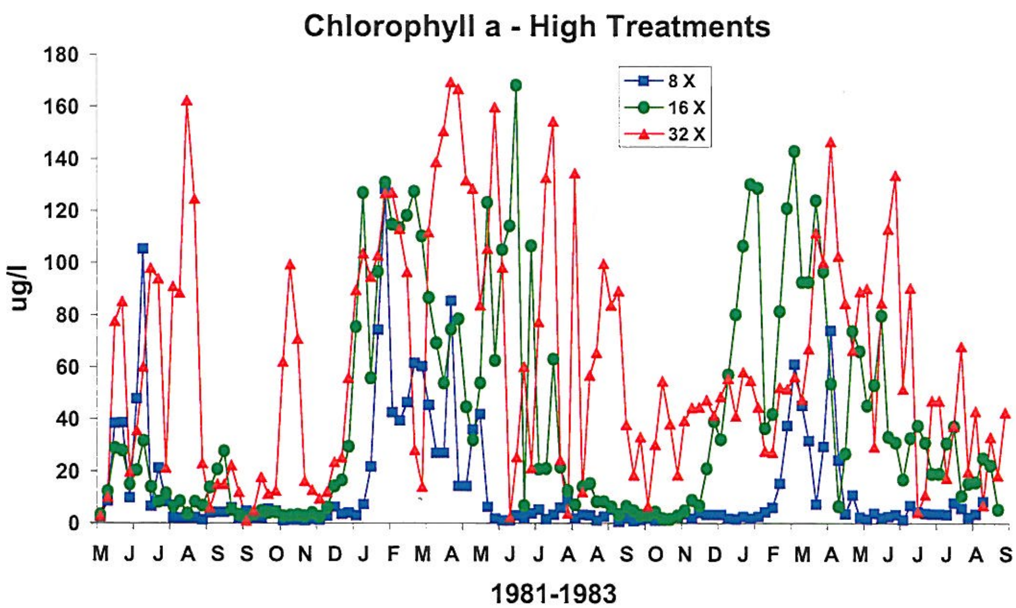

Figure 9: Phytoplankton biomass in the high treatment tanks, May 1981 – September 1983.

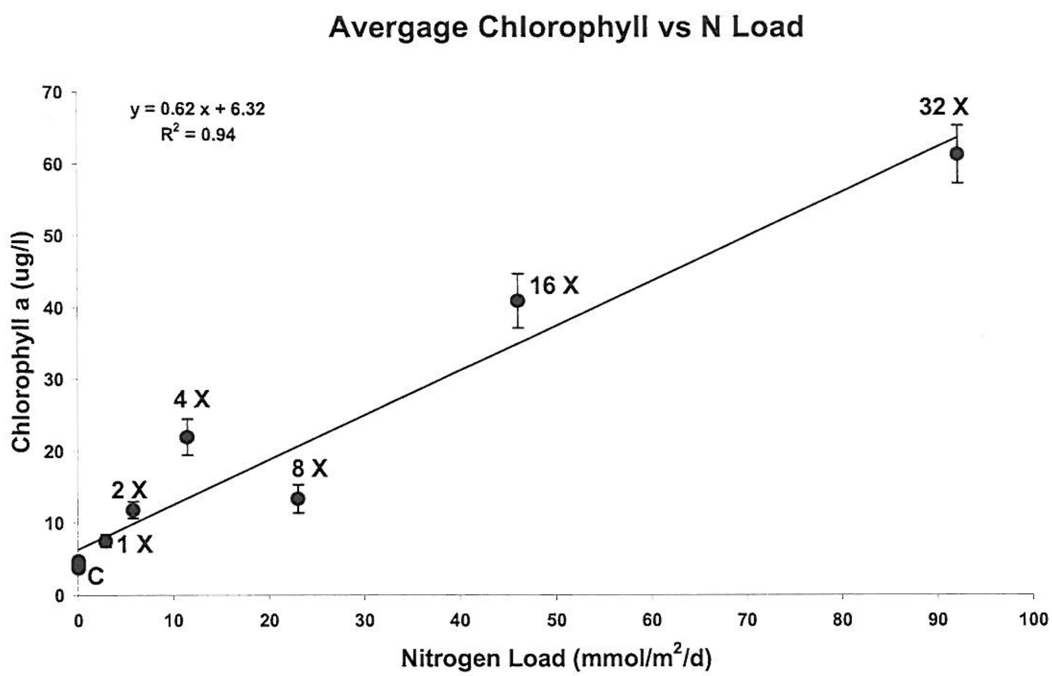

Figure 10: Mean phytoplankton biomass as a function of loading from the experiment.

- At higher loading rates (> 8x), light penetration depth decreases in the upper water column as a result of shading by phytoplankton to the point where phytoplankton growth becomes limited by light, not nitrogen. In essence, nutrients are over-abundant at these enrichments.

Ambient nitrogen concentrations

- The MERL tanks show a linear increase in the mean concentration of inorganic nitrogen in the tanks as a function of the loading rate (Figure 11).

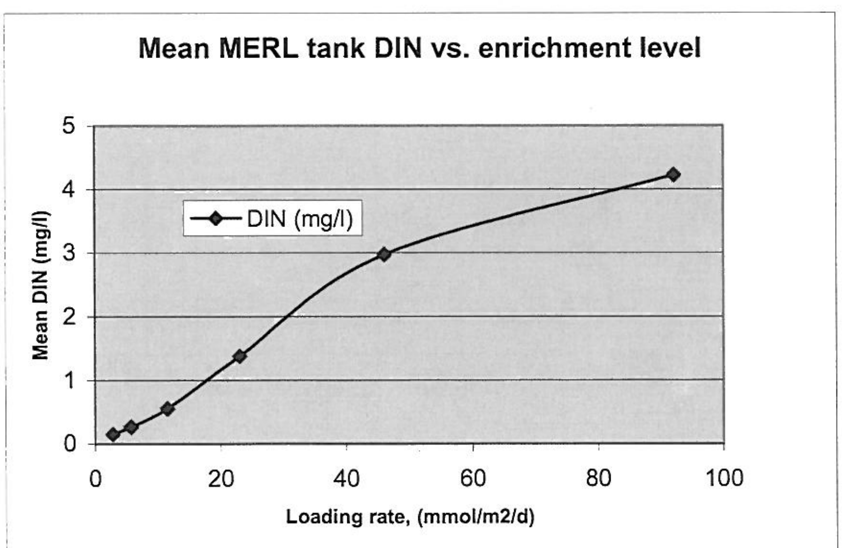

Figure 11: Relationship between tank DIN concentration and N-loading rate.

HOW DOES THE PROVIDENCE AND SEEKONK RIVER SYSTEM COMPARE WITH THE MERL EXPERIMENT?

The present condition of the Providence and Seekonk Rivers and sources is based on the 1995 – 1996 study by DEM Water Resources. The study consisted of measurements of loading from the principal sources to the area, which included the three WWTFs and the five major tributaries. The frequency of sampling of the sources was proportional to the magnitude of the source. The four principal sources: Bucklin and Fields WWTFs, and the Blackstone and Seekonk Rivers, were sampled more than 50 times during the two years. Loads included flows taken either from plant records or USGS gages.

Eleven snapshots of water properties were also collected during the May- October time frame during the two years, six during 1995 and five during 1996. The estuary surveys included high and low tide measurements of hydrographic properties (temperature, salinity, DO) and chemical (chlorophyll-a, nitrogen, phosphorus, and silicon) at sixteen stations. Production and light penetration measurements were made across the photic (light penetration) zone at three stations. The surveys measured nearly all the parameters measured during the MERL experiments.

The first basis for comparison is in terms of loadings per unit area. Loadings used for the MERL experiment were represented in units of mass per unit area per day, with the 1X case representing the estimated total inorganic nutrient (e.g. dissolved inorganic nitrogen (DIN)) load to the entirety of Narragansett Bay from all sources (2.88 mmole/m2/day or 4.03E-05 kg/m2/day). For the 1995-1996 study period, loadings to the Providence and Seekonk Rivers were estimated by combining the observed ammonia (NH_3) and total nitrate ($NO_2 + NO_3$) concentrations with concurrent flows (values scaled to the mouths of tributaries). The Providence and Seekonk Rivers were next divided into four reaches following Chinman and Nixon (1985), with the area of each reach including those of upstream reaches. For example, Element 2 in this analysis (north of Fields Point) would include loads and areas to the upstream Element 1 (Seekonk River). The surface area of each element is listed in Table 2. For future reference, the load to each element corresponding to the 2x loading condition is also included in the table.

Table 2: Surface area by reach and daily load to the reach for the 2x load condition.

Element	Area (m2)	Load at 2X (mmole/day)	Load at 2X (kg/day)
Seekonk	2.81E+06	1.62E+07	226.3
Fields	5.81E+06	3.34E+07	468.2
Bullocks	1.43E+07	8.26E+07	1156.5
Providence R.	2.41E+07	1.39E+08	1945.7

A comparison of loads per unit area from the 1995-1996 DEM study to the MERL enrichment gradient experiment is presented in Figure 12. The figure shows that on a unit area basis, using measurements from the 1995-1996 DEM Study, the Providence - Seekonk River system receives loads at a rate between the 4X and 8X case (6X). The Seekonk River receives loads at a rate between the 16X and 32X cases (24X). It is worth noting that the majority of the DEM measured loads for the tributary rivers were collected during typical summer season flows and as such do not account for

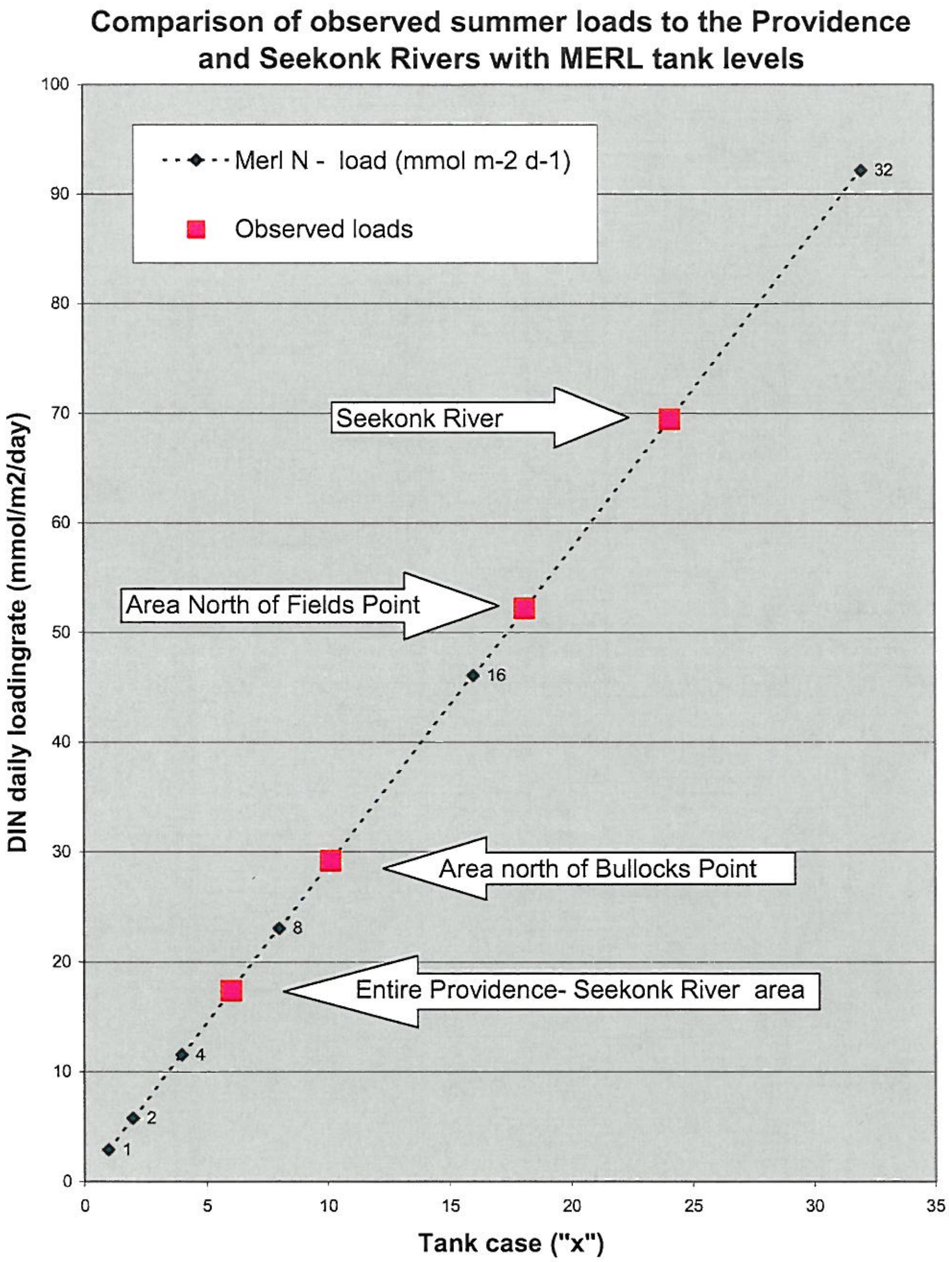

Figure 12: Comparison between observed loads per unit area to reaches of the Providence and Seekonk Rivers with the MERL enrichment experiment tanks.

wet weather loadings. Neither the DEM data nor the MERL experiments directly accounted for atmospheric deposition to the Bay surface. The DEM data also do not account for CSO loads, or for storm runoff entering downstream of the mouths of the tributaries.

The dissolved oxygen and chlorophyll data derived from Sea-Bird data supported by surface and bottom water grabs from the 1995-1996 DEM surveys, averaged by depth from the daily high and low tide surveys, are shown as a function of distance along the river and depth in Figures 13 through 16. DO and chlorophyll-a data averaged for the top 2 m of the water column for station 5 located at the north end of Fields Point are shown in Figures 17 and 18. The 1995 data show a system that is alternating between extremes of oxygen and chlorophyll during the four mid-summer surveys. Beginning on June 29, DO is well above saturation in the upper water column throughout the length of the system. June 29 chlorophyll levels are very high, exceeding 200 ug/L in the Seekonk River and 100 ug/l in Providence Harbor. Three weeks later (July 20), with no significant rainfall, and Blackstone River discharge down near its 7Q10 value (the lowest 7-day mean discharge over a 10-year period), the bottom waters of the Seekonk River are essentially anoxic and the area upstream of Sabin Point is hypoxic (3.80 mg/l at the surface, Fields Point). Chlorophyll levels are near zero throughout the area, except near the mouth of the Providence River. Three weeks later on August 10, the conditions of June 29 have returned: supersaturated DO levels near the surface, and relatively high (20-30 ug/l) chlorophyll levels in the upper river. Two weeks later on August 24, DO has again dropped to low values. The entire area is hypoxic, and is anoxic near the bottom in the upper reaches. Surface DO at Fields Point (Figure 17) is 3.4 mg/l on August 24. Levels only occasionally exceed 4 mg/l down to Conimicut Point. Chlorophyll levels remain high at some locations in the river, with peak values above 30ug/l between the south end of Fields Point and Sabin Point. On September 21, DO levels have increased somewhat, but are still low near the bottom in the Seekonk River.

In summary, the behavior of dissolved oxygen during 1995 may be characterized as swinging between extremes, in a manner qualitatively similar to that of the higher enrichment tanks (e.g. 16X and 32X). In general, dissolved oxygen levels were not sufficient to support fish populations near the surface during many periods in 1995.

Mid-summer 1996 dissolved oxygen levels in the Providence River appear to be more stable, This stability appears to result from vertical stratification caused by higher river flow that occurred during that summer. Bottom water oxygen levels remained below 4 mg/l to the mouth of the Providence River, probably between mid-June through late September. Values near the bottom of the channel (below 10m depth) were typically near zero down to Sabin Point during this period. Chlorophyll-a levels were lower in 1996; peak values were an order of magnitude lower, probably because flushing times were low.

The field chemistry data are summarized in Table 3 below as averages by station for the center of channel stations for both years. When compared to the MERL results and the MA guidelines discussed below, the Providence River concentration data indicate that the area is enriched. TN levels are above 0.4 mg/l throughout the area, up to nearly 1.5 mg/l at station 1. DIN concentrations are significantly greater than a 10 uM (0.14 mg/l) guideline used by Massachusetts. Mean chlorophyll levels obtained from water samples exceed 10 ug/l at all stations with the exception of 4 at Fox Point, and increase to above nearly 30 ug/l in the Seekonk River, which approached the 16x MERL tank condition.

Mean DIN concentrations observed in the Providence and Seekonk Rivers were significantly lower than those seen in the MERL experiment for an equivalent loading rate per unit area. For example, DIN at station 1 in the upper Seekonk River was less than 1 mg/l. An expected concentration from the MERL data in Figure 11 for that location would be approximately 3.9 mg/l. This difference may possibly result from the shorter characteristic flushing time of the Providence River. Empirically derived relationships between freshwater inflow and flushing time developed by Asselin (1991) indicate that the mean residence time of fresh water in the Providence and Seekonk River during the May- October periods of 1995 and 1996 would be about 3.5 days. This is significantly shorter than the 27-day time used by MERL. The higher removal rate by flushing would account for the difference. DIN uptake by macroalgae and denitrification in the bottom waters are additional reasons. Significant areas flanking the dredged channel in both rivers are shallow, and significant growth of macroalgae occurs in the area each year. Enrichment experiments in shallow mesocosms have observed a similarly diminished DIN buildup in the water column that is possibly connected to uptake by macroalgae and benthic flora (Nixon et al, 2001). Nixon et al also suggests that in shallow systems, the residence time of nitrogen may be much longer than a conservative substance, such as fresh water. The disparity between the observed and predicted DIN shows that the MERL system is not a perfect analog. We feel, however, that the other relationships make the connection adequate.

Table 3: Means of the 1995-1996 DEM estuary chemistry data.

	Station 10.2	Station 9.2	Station 8	Station 7	Station 6.2	Station 5	Station 4	Station 3	Station 2	Station 1
River Reach	**Upper Bay**	**Lower River**	**Bullocks Pt. Reach**			**Fields Point Reach**		**Seekonk River Reach**		
NH4 (mg/l)	0.06	0.08	0.12	0.16	0.18	0.25	0.28	0.37	0.37	0.31
NO3+NO2 (mg/l)	0.06	0.08	0.12	0.11	0.19	0.13	0.16	0.41	0.54	0.65
DIN (mg/l)	0.12	0.16	0.24	0.27	0.37	0.37	0.44	0.78	0.92	0.96
TP Nitrogen (mg/l)	0.10	0.11	0.09	0.08	0.10	0.05	0.05	0.09	0.11	0.10
TN (mg/l)	0.43	0.47	0.54	0.56	0.73	0.63	0.66	1.13	1.26	1.46
PO4 (mg/l)	0.06	0.08	0.09	0.10	0.13	0.14	0.15	0.23	0.25	0.22
TP (mg/l)	0.10	0.11	0.12	0.13	0.17	0.17	0.18	0.26	0.31	0.29
BOD5 (mg/l)	2.18	2.86	2.60	3.61	4.75	2.64	2.82	3.46	2.17	5.09
Chl-a (ug/l)	15.33	16.42	15.68	14.93	23.56	11.16	8.09	14.14	17.52	27.82

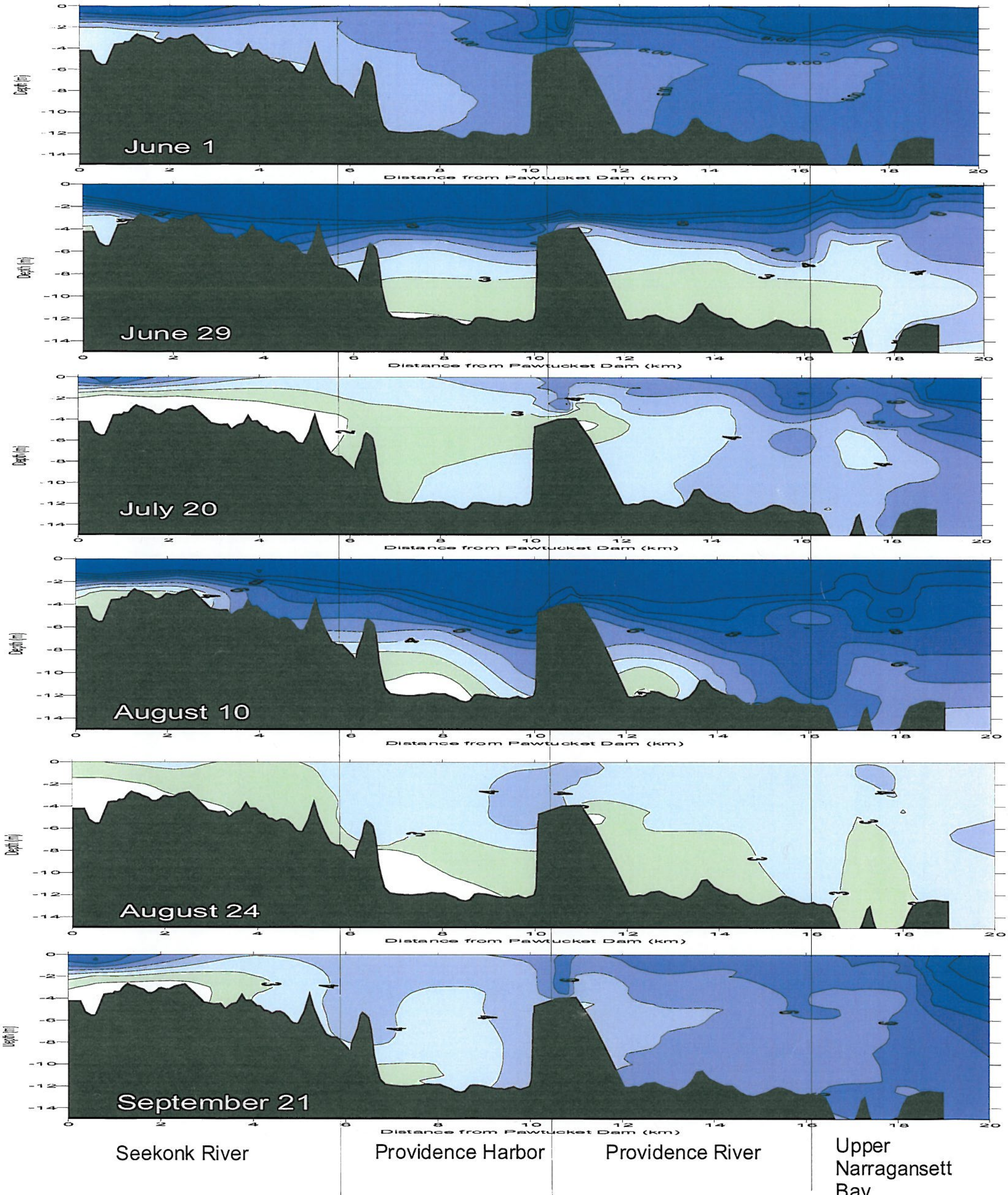

Figure 13: Tidally averaged dissolved oxygen vs. depth and location during the 1995 surveys. White areas:<2 mg/l. Green areas: 2-3 mg/l. Blue areas >3 mg/l at 1mg/l increments.