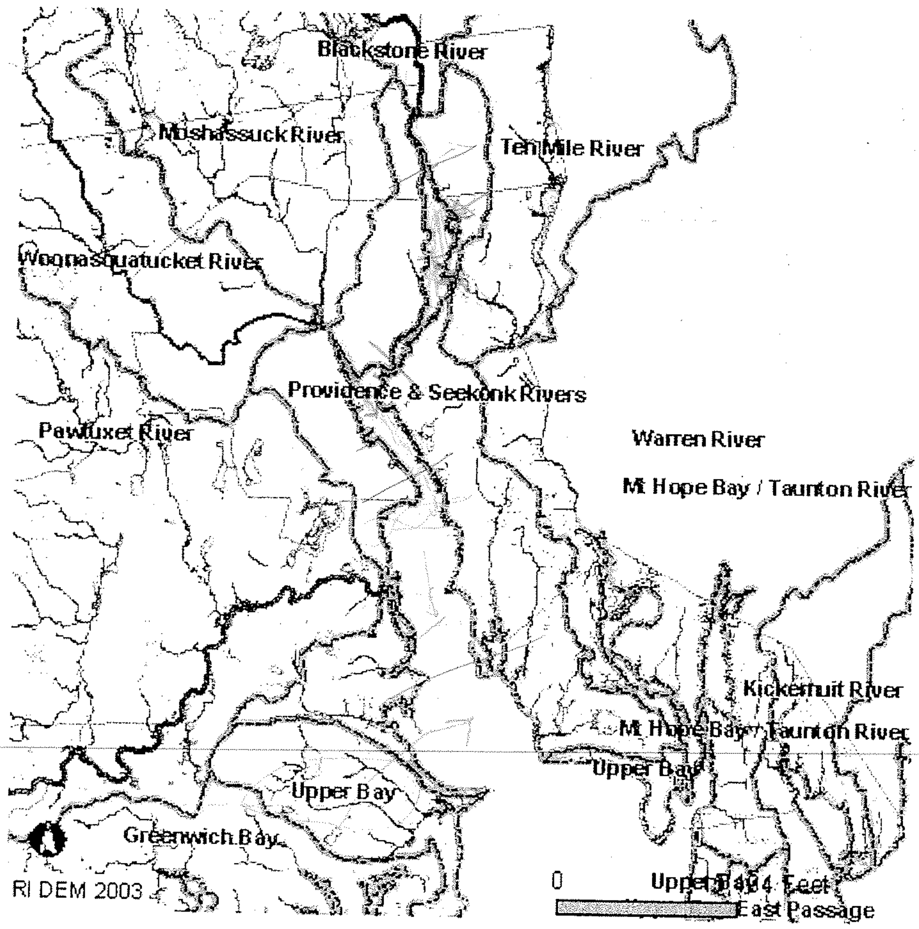
EVALUATION OF NITROGEN TARGETS AND WWTF LOAD REDUCTIONS FOR THE PROVIDENCE AND SEEKONK RIVERS



RHODE ISLAND DEPARTMENT OF ENVIRONMENTAL MANAGEMENT
OFFICE OF WATER RESOURCES
DECEMBER 2004

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

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:

<u>Dissolved oxygen:</u>
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.

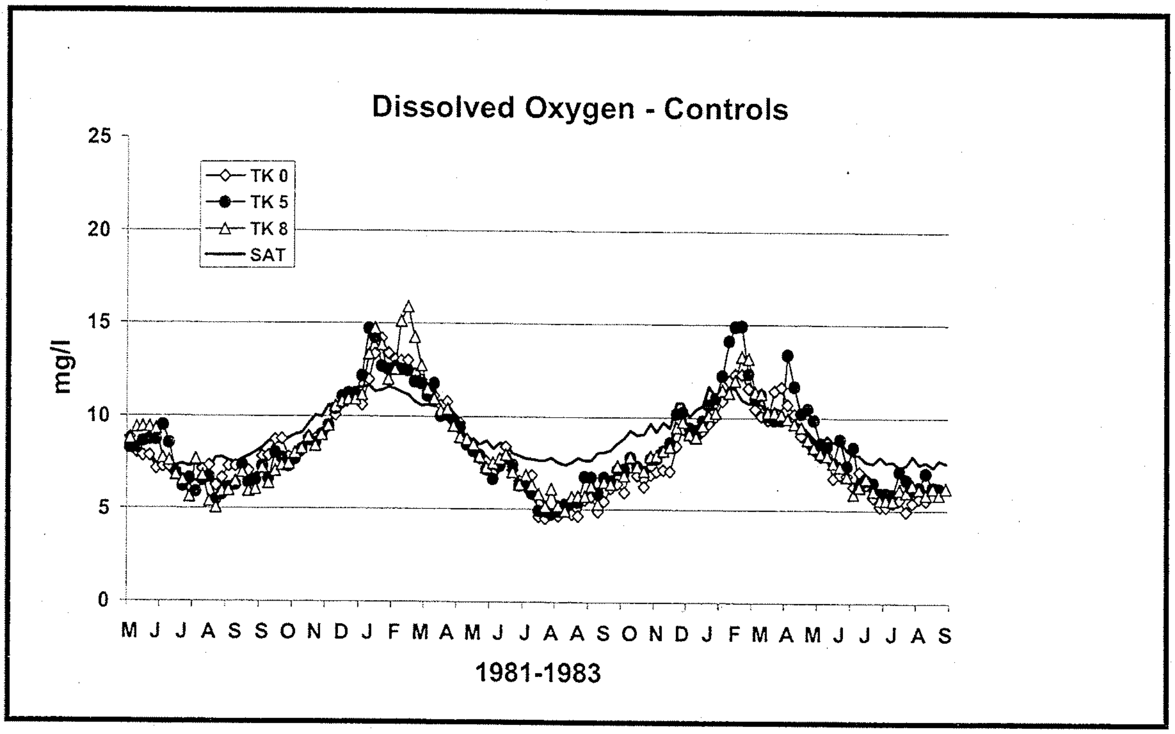


Figure 1: DO for the control tanks, May 1981 – September 1983.

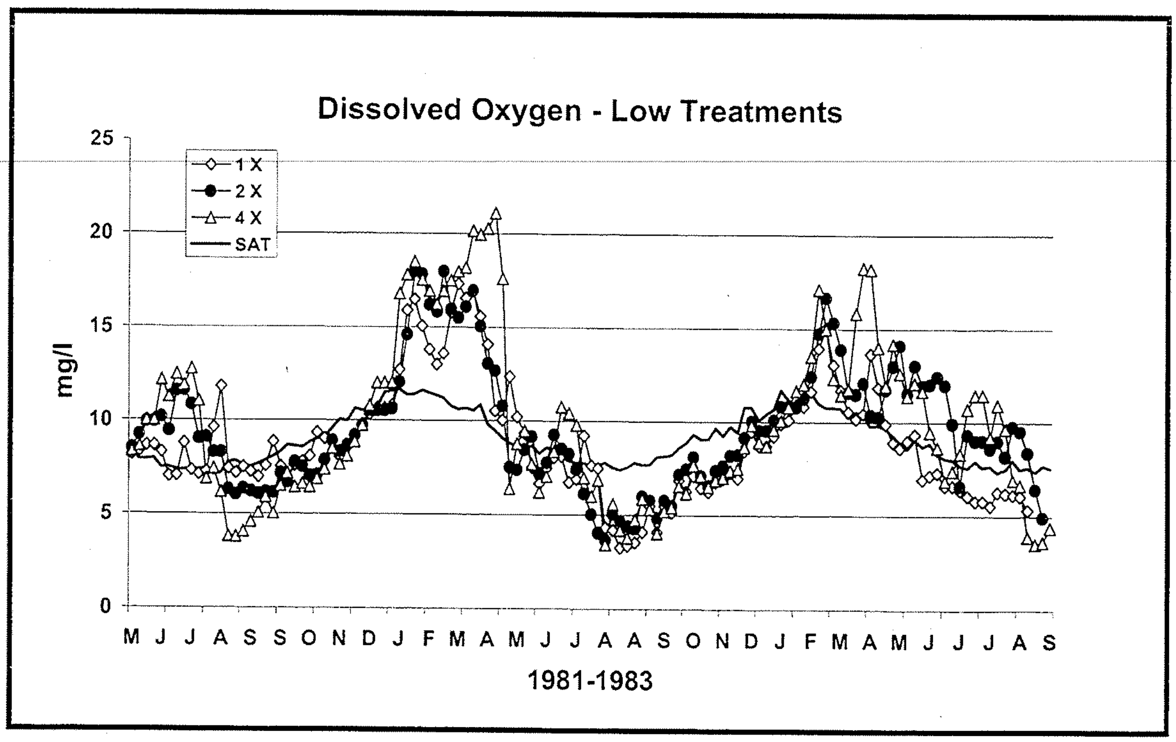


Figure 2: DO for the low level treatment tanks, May 1981 – September 1983.

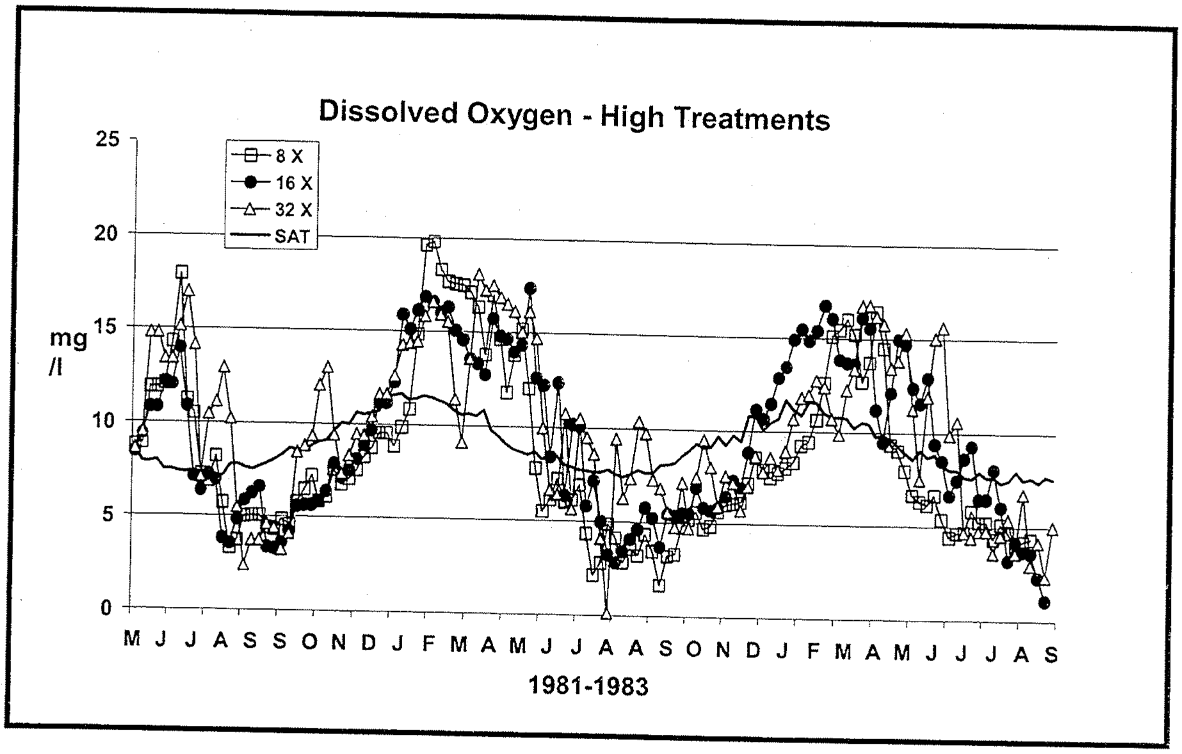


Figure 3: DO for the high level treatment tanks, May 1981 – September 1983.

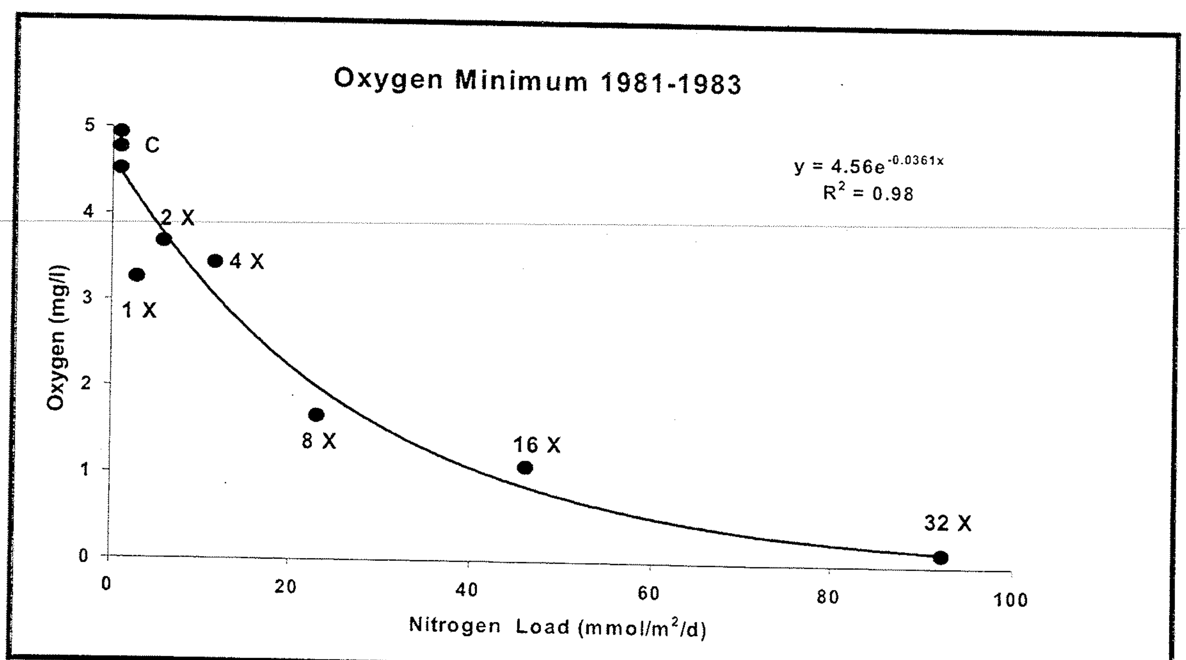


Figure 4: The relationship between the inorganic nitrogen loading rate and minimum observed oxygen concentration, which shows that the oxygen minimum drops rapidly with increasing loadings.

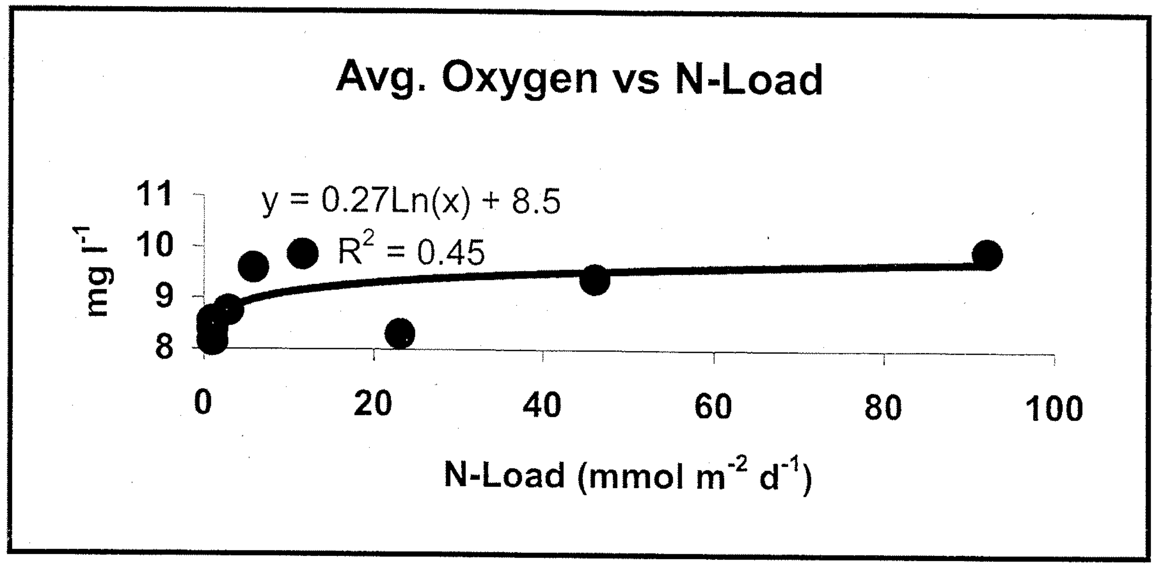


Figure 5: Graph of mean MERL tank DO as a function of loading, showing that the average DO goes up slightly as nutrient loadings are increased.

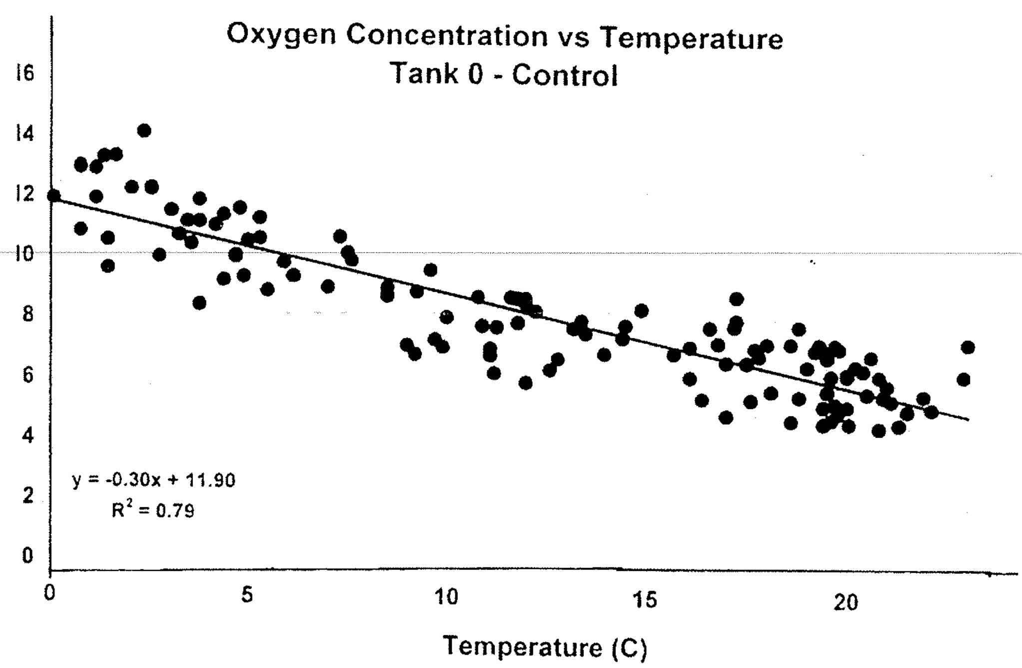


Figure 6: The relationship between DO and temperature in a control tank.

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).

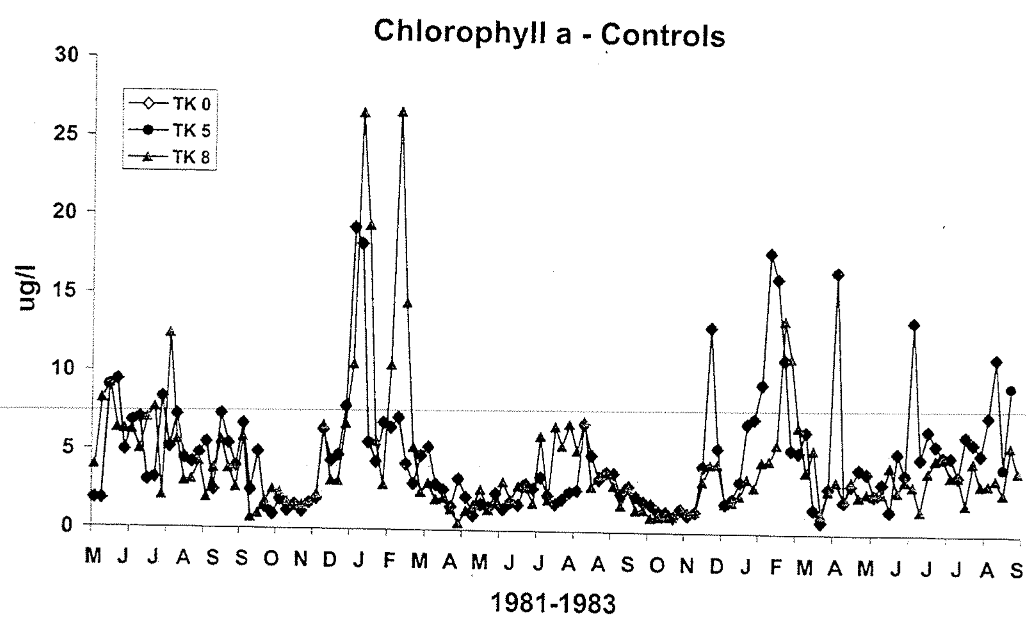


Figure 7: Phytoplankton biomass in the control tanks, May 1981 – September 1983.

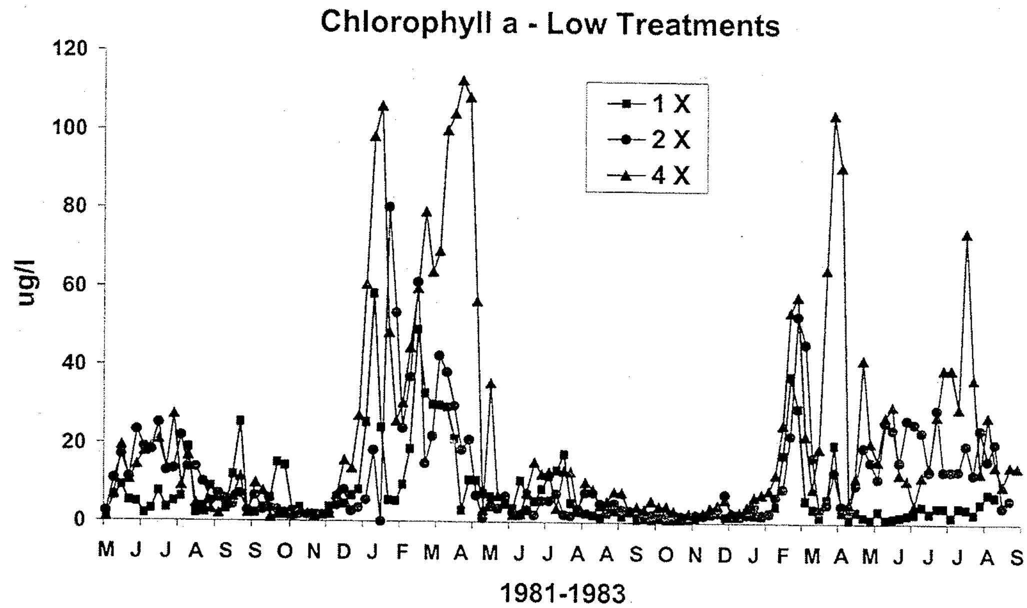


Figure 8: Phytoplankton biomass in the low treatment tanks, May 1981 – September 1983.

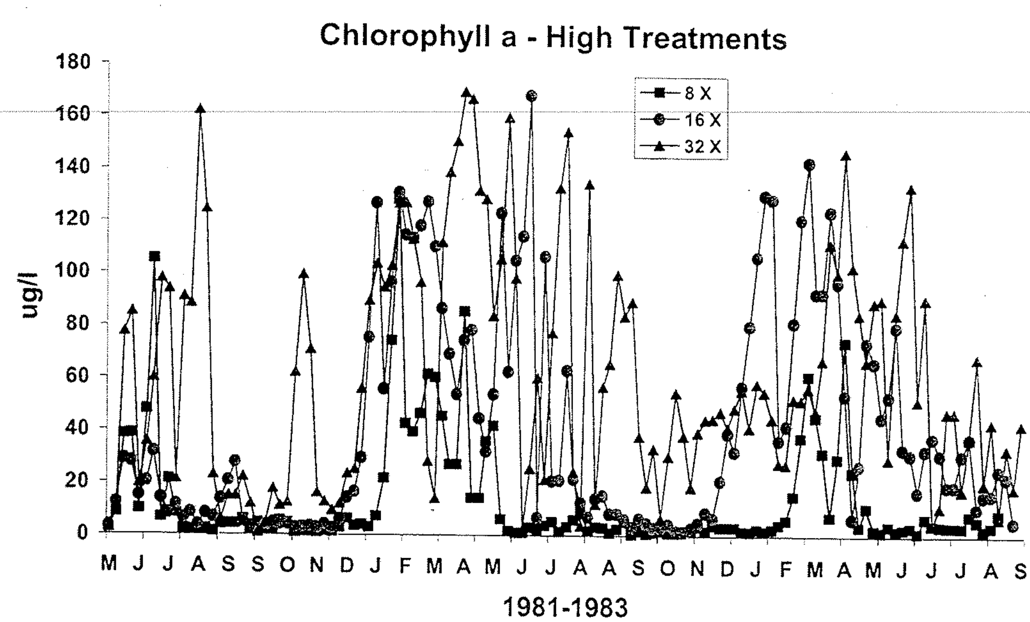


Figure 9: Phytoplankton biomass in the high treatment tanks, May 1981 – September 1983.

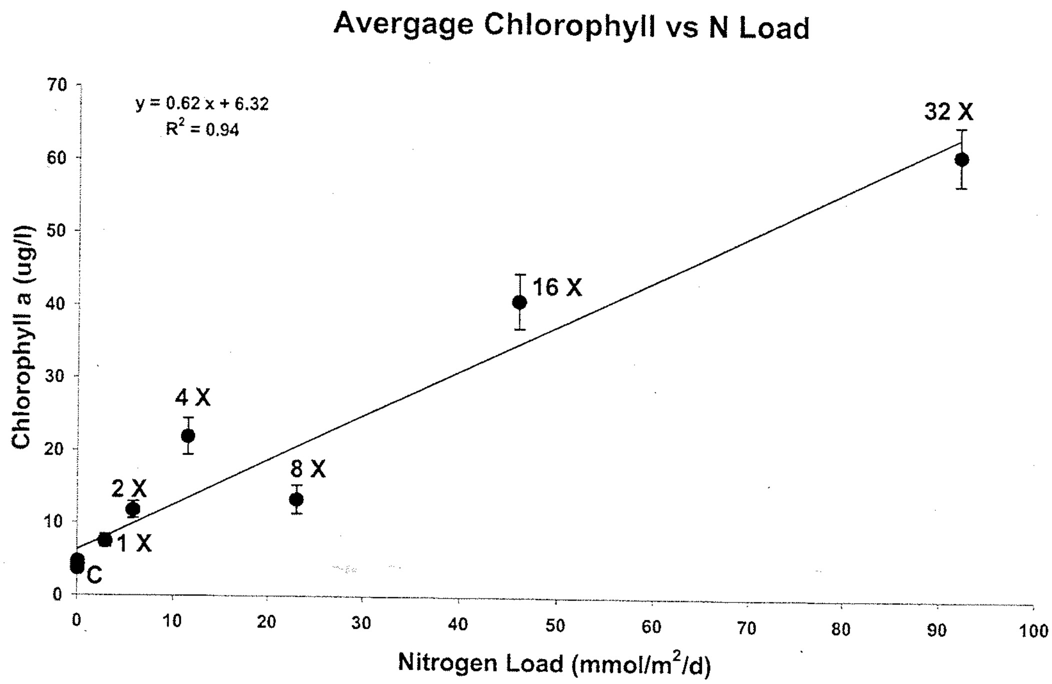


Figure 10: Mean phytoplankton biomass as a function of loading from the experiment.

- 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.

<u>Ambient nitrogen concentrations</u>

- 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).

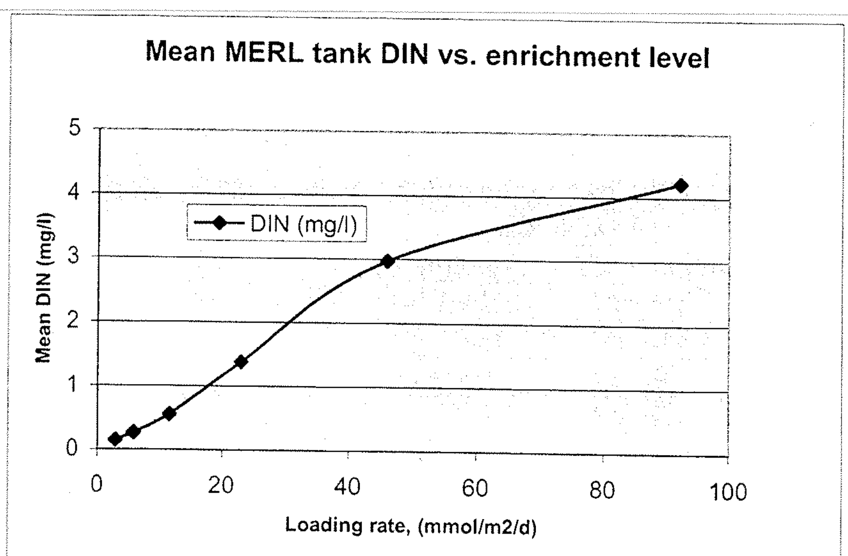


Figure 11: Relationship between tank DIN concentration and N-loading rate.

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

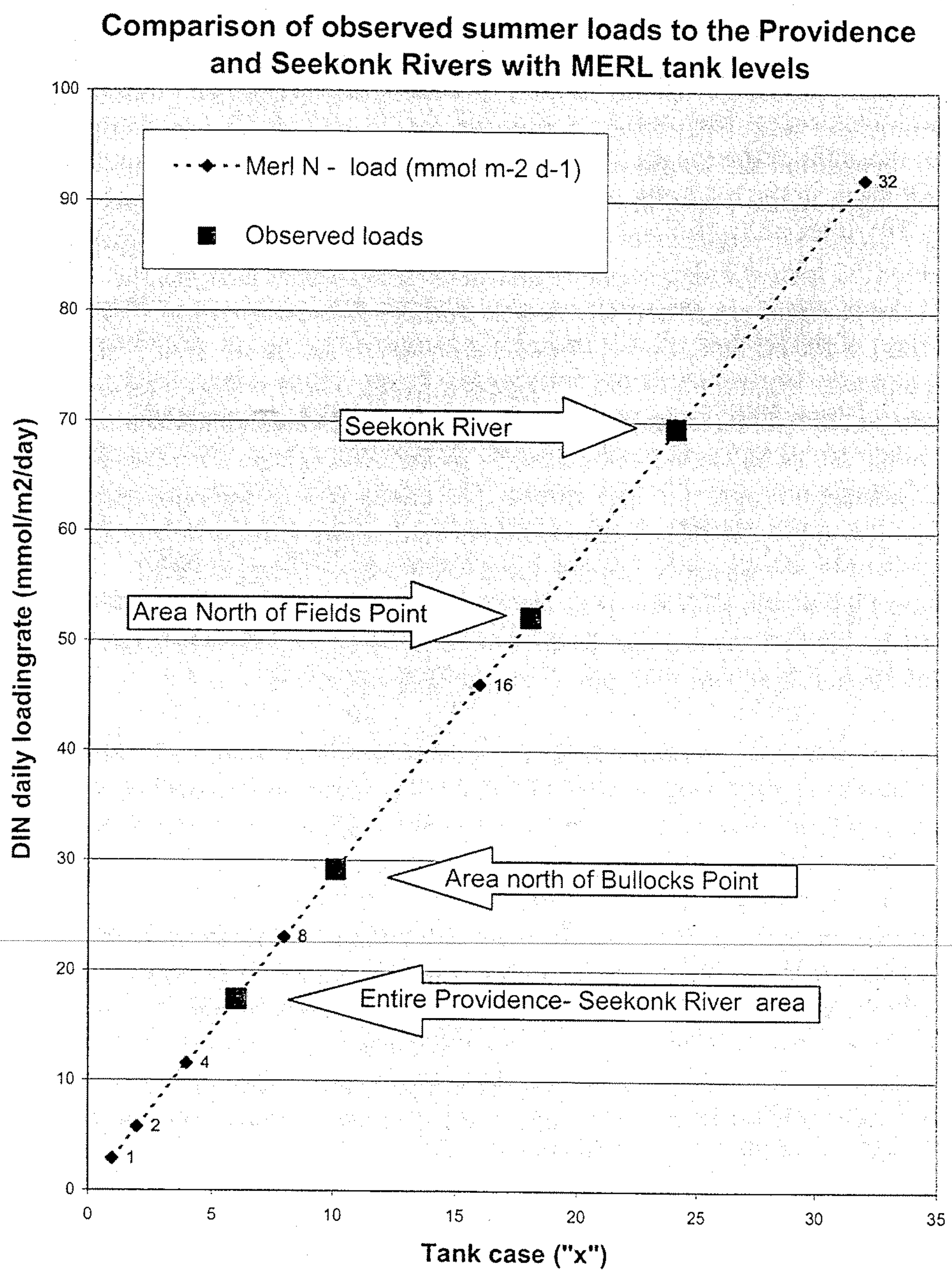


Figure 12: Comparison between observed loads per unit area to reaches of the Providence and Seekonk Rivers with the MERL enrichment experiment tanks.

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

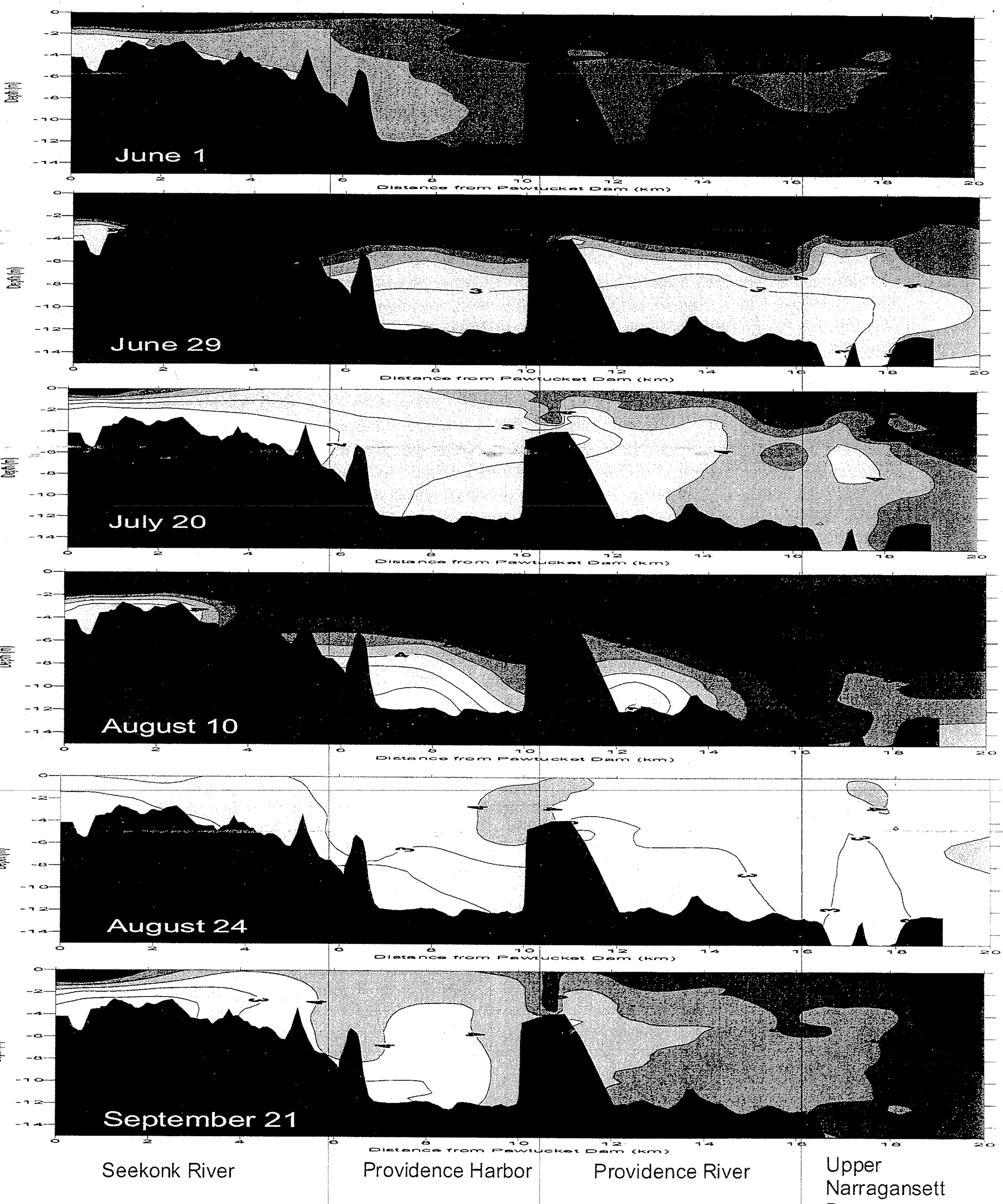


Figure 13: Tidally averaged dissolved oxygen vs. depth and location during the 1995 surveys. White areas:<2 mg/l. Green areas: 2-3 mg/l. Blue areas >3 mg/l at 1mg/l increments.

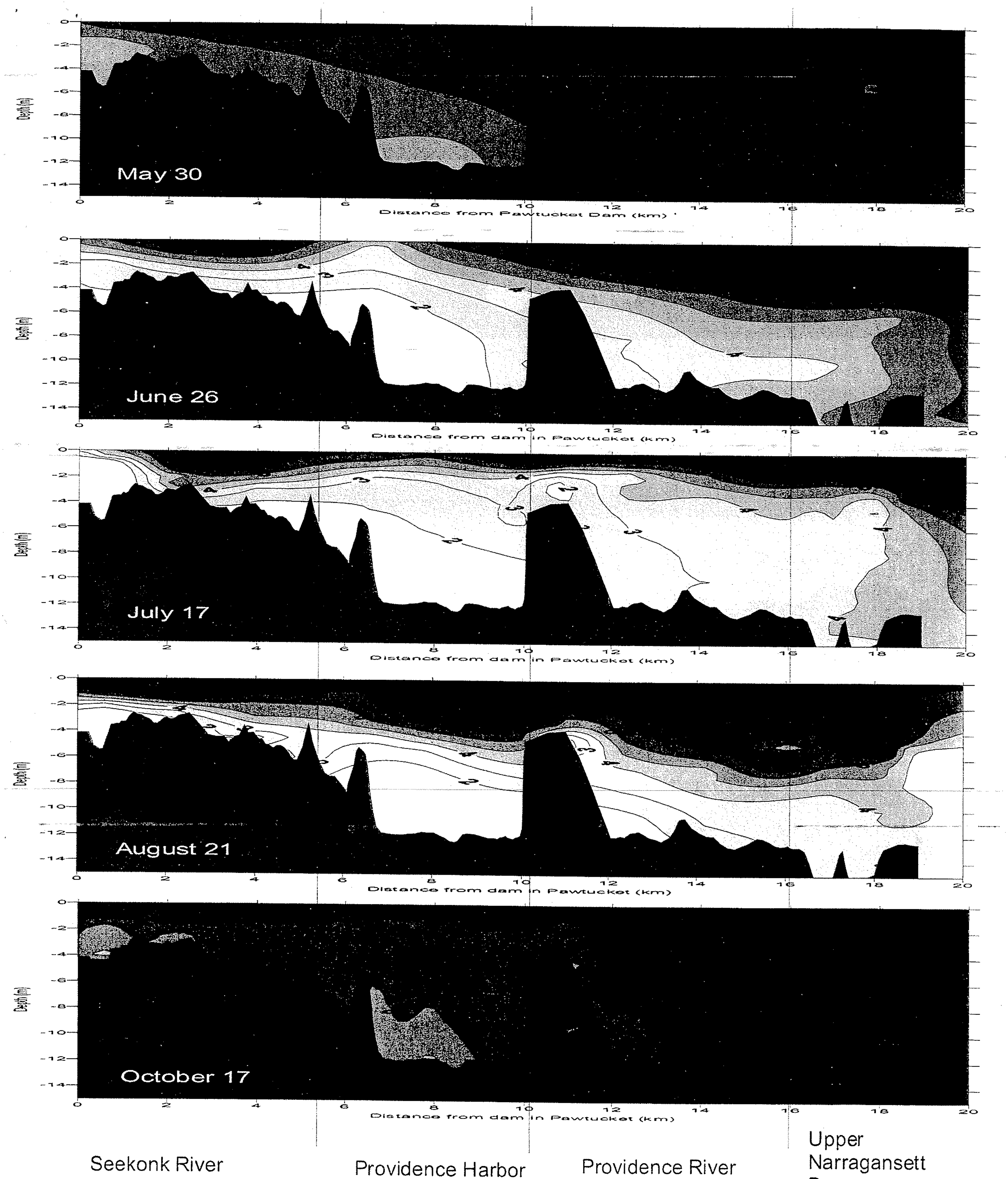


Figure 14: Tidally averaged dissolved oxygen vs. depth and location during the 1996 surveys
White areas:<2 mg/l. Green areas: 2-3 mg/l. Blue areas >3 mg/l at 1mg/l increments.

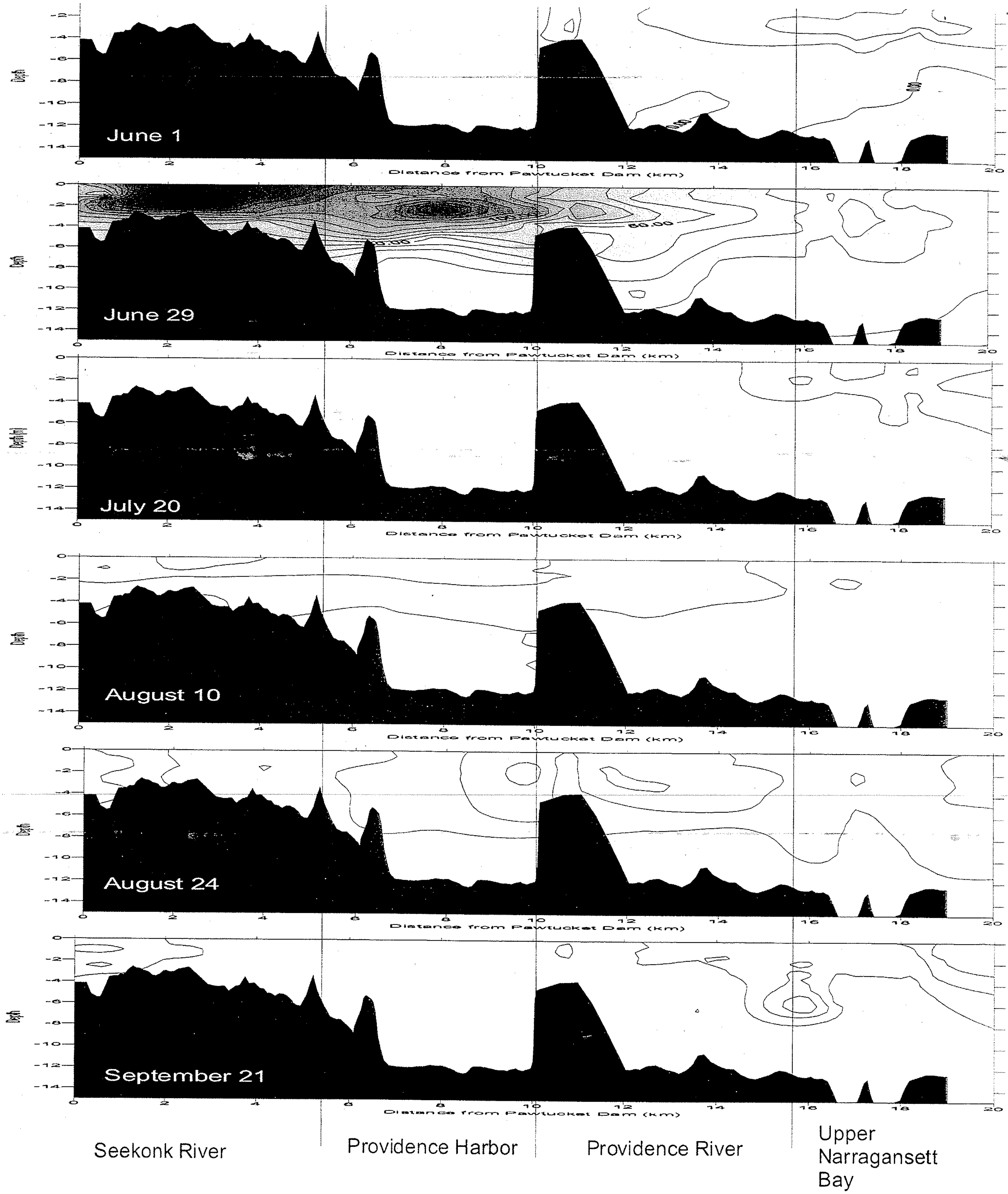


Figure 15: Tidally averaged chlorophyll-a vs. depth and location during the 1995 surveys
Isopleths are at 10 ug/l increments

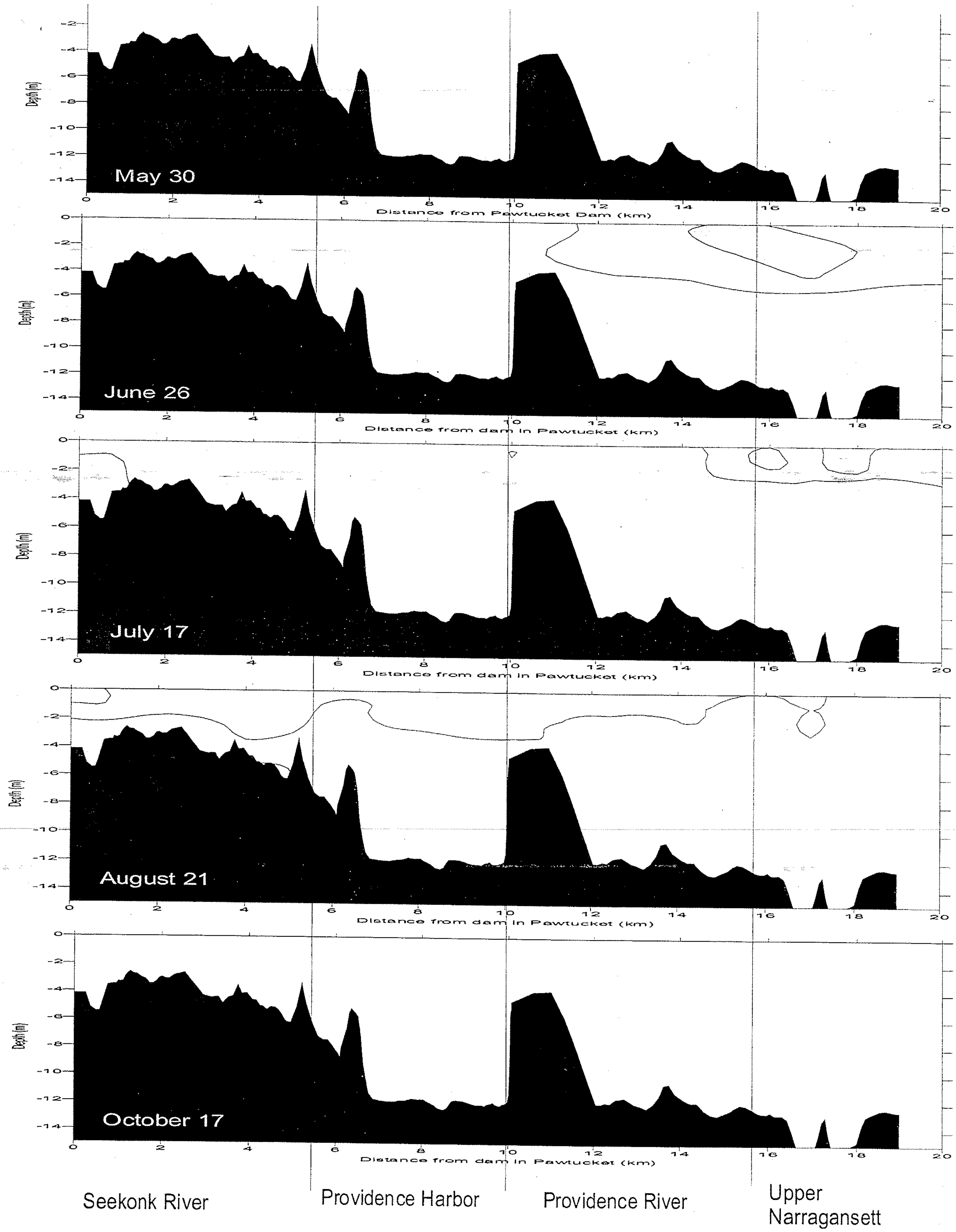


Figure 16: Tidally averaged chlorophyll-a vs. depth and location during the 1996 surveys. Isopleths are at 10 ug/l increments.

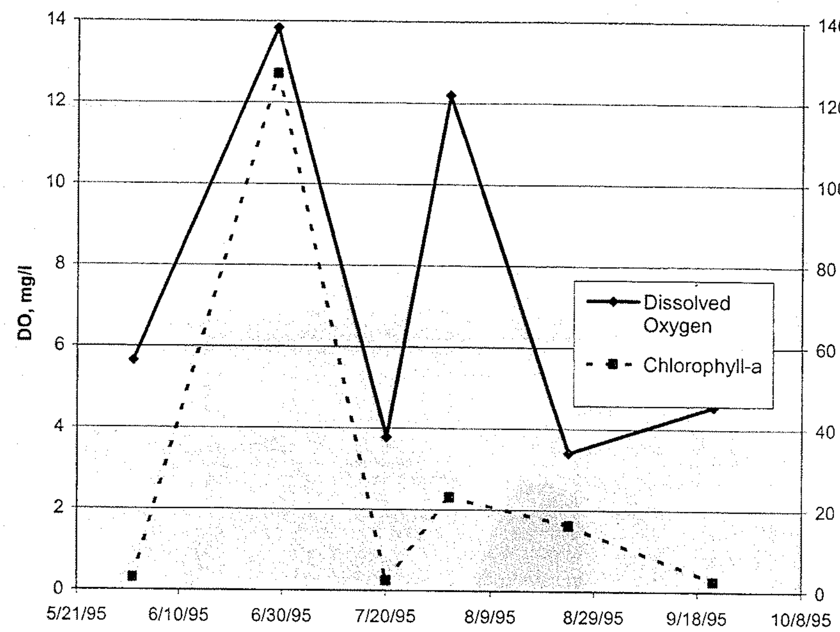


Figure 17: Tidally averaged dissolved oxygen and chlorophyll-a in the top 2m of the water column in Providence Harbor during the summer of 1995

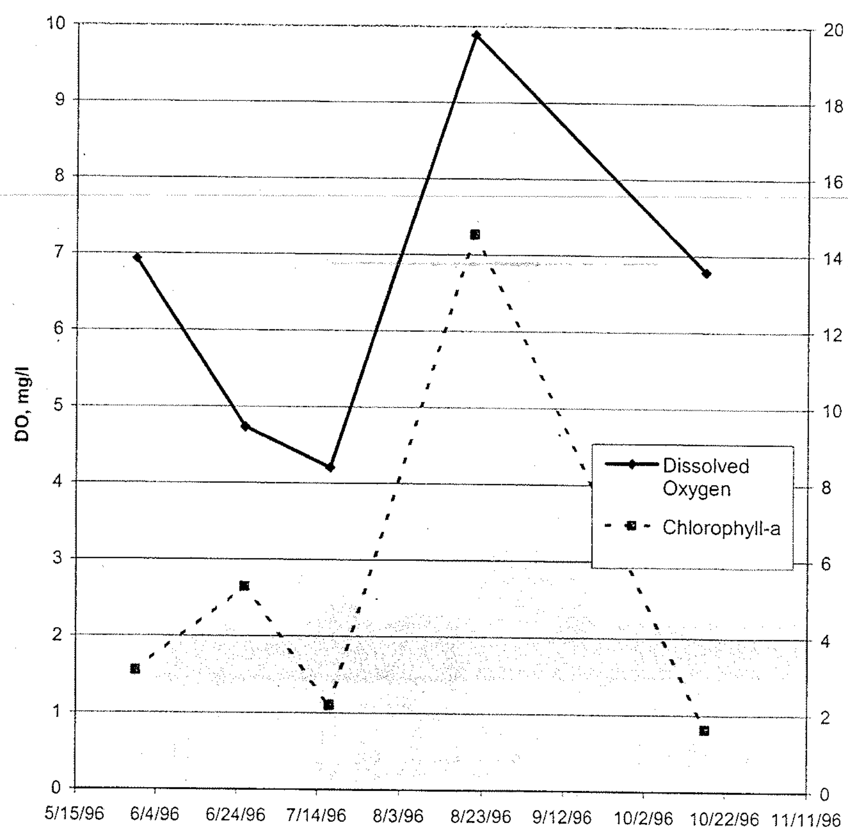


Figure 18: Tidally averaged dissolved oxygen and chlorophyll-a in the top 2m of the water column during the summer of 1996

USING THE MERL RELATIONSHIPS TO PROJECT THE IMPLICATIONS OF FUTURE NITROGEN LOAD REDUCTIONS TO THE PROVIDENCE AND SEEKONK RIVERS

As noted in the Initial Report From the Nutrient and Bacteria Pollution Panel of the Governor's Bay and Watershed Planning Commission, several analyses have been conducted which agree that wastewater treatment plants are the major source of nitrogen to Narragansett Bay (Nutrient and Bacteria Pollution Panel, 2004). This section presents a summary of an analysis that DEM has conducted to evaluate outcomes for reducing nitrogen levels.

Considerations Regarding WWTF loading reductions

The Long Island Sound TMDL for DO set the degree of nutrient reduction at a WWTF based on the relative environmental impact of each discharge. This issue was addressed in the Long Island Sound Dissolved Oxygen TMDL (NYDEC and CTDEP, 2000) by establishing two "equivalency factors" to account for the loss of nitrogen between the point of discharge and the point of impact. These were: 1) attenuation during tributary river transport, called river delivery factors, and 2) transfer efficiency from the "edge-of-Sound" to the area of most significant degradation.

River delivery factors are predicated on the idea that some degree of nitrogen removal due to permanent uptake or denitrification occurs in the river between the WWTF discharge and the mouth. It is expressed as the percentage of the point source load discharged to the river that reaches the Sound. In the Long Island Sound Study, river delivery factors ranged between 52% – 90%. River delivery factors may increase as nutrient inputs are restricted to control low dissolved oxygen and excessive algae growth in the rivers. Reductions in WWTF phosphorus inputs have been required and are in various stages of completion along the Blackstone and Pawtuxet Rivers.

Blackstone River

Detailed source and river loads (i.e. concurrent WWTF and river data) were computed as part of the 1991 interstate Blackstone River Initiative study. Based on sampling conducted during three sampling surveys (July, August and October), the load discharged from the mouth of the Blackstone River into the Seekonk River is estimated to range from 27% to 84% (average 60%) of the summed nitrogen loads from the Woonsocket WWTF and the Upper Blackstone Water Pollution Abatement District WWTFs. Based on DEM's 1995 and 1996 sampling at the mouth of the Blackstone and monthly average WWTF discharge monitoring report data, 87% of the loading from the two sources is discharged from the Blackstone River. Stated another way, reducing the total nitrogen from the WWTFs to 8 mg/l is equivalent to 7.0 mg/l discharged near the mouth of the Blackstone River. The difference is attributable to uptake and denitrification along the length of the river. Given the large range observed during the Blackstone River Initiative, and since concurrent WWTF and river data is not available for the other tributaries rivers the 1995 – 1996 data was used to calculate delivery factors for all tributaries to the Providence and Seekonk Rivers.

Pawtuxet River

Attenuation of the West Warwick, Warwick and Cranston WWTFs loading is anticipated when discharged from the mouth of the Pawtuxet River into Pawtuxet Cove which in turn discharges to the Providence River at Pawtuxet Neck. Using the method described above, it was estimated that 82% of the WWTF load is discharged from the mouth of the river.

Ten Mile River
In the Ten Mile River, the DIN discharge to the Seekonk River was found to be 61% of the concurrent load estimate from the Attleborough and North Attleborough WWTFs using 1995-1996 flows. The Attleborough facilities did not monitor nitrogen during that period, so concentrations reported in 2000-2002 discharge monitoring reports (DMRs) were used to represent the facility loads.

Consideration of the transfer efficiency from the edge of the Providence and Seekonk Rivers acknowledges that areas of the Providence and Seekonk Rivers with the most severe hypoxia are located from the mouth of the Blackstone River to Gaspee Point. Although sufficient information is not available to quantitatively evaluate this "equivalency factor", a qualitative approach is also instructive.

Edge of the Seekonk River
Sources to the edge of the Seekonk River include the Blackstone River, the Ten Mile River and the Bucklin Point WWTF. Given the close proximity of these sources it is reasonable to conclude that on a unit loading basis, these sources equally impact the Seekonk River. As such it is not appropriate to establish transfer efficiency factors for these sources.

Edge of the Providence River
Significant nitrogen sources to the edge of the Providence River include the Seekonk River, Fields Point WWTF, East Providence WWTF and Pawtuxet Cove. Based on the close proximity of the Seekonk River, Fields Point WWTF and East Providence WWTF to one another and to the areas of most severe hypoxia, it is reasonable to conclude that on a unit loading basis, all sources cause equal environmental impacts. The Pawtuxet River discharges to Pawtuxet Cove, which then empties into the Providence River at the southern extent of the area of severe hypoxia. As a result, the impact of nutrient loadings from Pawtuxet Cove would qualitatively expected to be less than that those from sources to the edge of the Providence River or to the edge of the Seekonk River.

Loads from upstream WWTFs in the Pawtuxet, Blackstone and Ten Mile Rivers
WWTF loads to the tributary rivers were calculated using Discharge Monitoring Report (DMR) data collected May – October 1995-1996. Inorganic nitrogen data were not collected by the Upper Blackstone or Ten Mile facilities during that period. As a consequence, data collected for May through October 2000 - 2002 were used to represent the facility loads from the Upper Blackstone facility (UBWPAD) in Worcester, Attleborough and North Attleborough WWTFs.

Loads reaching the mouths of the rivers from the WWTFs were calculated in two ways for this analysis. The first approach assumed that the DIN load released from the facilities reached the mouth of each river with no loss or uptake in the river. This term was assumed to be representative of the case where either no denitrification was occurring, or where nitrogen was not accumulating annually in the bottom sediments of the river. The second approach assumed that some net uptake losses were occurring in the rivers. This loss term was calculated as a percentage of the combined plant load (other watershed sources, including smaller WWTFs in the upper Blackstone are assumed to be negligible), based on observed or estimated plant loads during the summer months of 1995 – 1996, and the loads observed leaving the mouths of the rivers. The ratios (load leaving river/load introduced by WWTFs) were 87%, 82%, and 60% for the Blackstone, Pawtuxet, and Ten Mile rivers, respectively.

A component of each plant's TN load was assumed to be refractory nitrogen. A refractory nitrogen concentration of 2.0 mg/l, the upper limit of the 0.5 to 2.0 mg/l range suggested in the literature (WEF and ASCE. 1992), was used as the mean difference between TN and DIN. The mean difference measured by DEM at Bucklin, Fields, and East Providence WWTFs during its 1995 – 1996 study was 1.4 mg/l. The DIN loadings from facilities in the tributary watersheds for each reduction scenario then equaled the product of the (TN-refractory N) concentration and plant flow. As an example, for the TN=5 case, the DIN load from a facility would be (3.0 mg/l) x (mean flow). For facilities not discharging directly to the Providence or Seekonk Rivers, and where river attenuation was assumed to occur, this load would be further reduced as described in the paragraph above. DIN loads from facilities directly on the Providence and Seekonk Rivers were calculated as the product of the (TN-refractory N) concentration and the mean flow.

Calculations were also made for the case in which projected loads were based on plant flows at 90% of their approved design flows. A comparison of WWTF data revealed that the average May-October 1995-1996 flows were 90% of the January-December 1995-1996 flows. WWTF design flows are listed in Table 4.

Table 4: Approved WWTF design flows and design flows used for the load evaluations.

WWTF Name	Approved Design Flow (MGD)	Estimated May-Oct Design Flow (MGD)
CRANSTON WWTF	20.2	18.18
EAST PROVIDENCE WWTF	10.4	9.36
NARRAGANSETT BAY COMM-BUCKLIN	31	27.9
NARRAGANSETT BAY COMM-FIELDS	65	58.5
WEST WARWICK WWTF	10.5	9.45
WARWICK WWT F	7.7	6.93
WOONSOCKET WWTF	16	14.4
UBWPAD	56	50.4
ATTLEBOROUGH WWTF	8.6	7.74
NORTH ATTLEBOROUGH WWTF	4.6	4.14

Base loads

Base nutrient loads from the Blackstone, Ten Mile, and Pawtuxet tributary rivers were calculated to establish a DIN concentration that would exist in the absence of wastewater treatment facilities. This minimum DIN concentration of 0.30 mg/l was derived from data collected in the north branch of the Pawtuxet River upstream of the WWTFs (Liberti, 1987). The base loads for each river were then calculated as the product of this concentration (0.30

mg/l) and the mean daily flow on the days samples were collected for the 95-96 TMDL study.. For the Blackstone River, the base load of 370 kg/day resulted from a mean discharge of 14.3 m3/s (discharge at Woonsocket scaled up to the value at the mouth). Estimated base loads calculated in a similar manner for the Ten Mile and Pawtuxet Rivers were 50 and 161 kg/day, respectively. These values were also used whenever the contributions from WWTFs reaching the mouths of the tributary rivers were less than the base loads.

Combining loads and areas

The impact of these loads on water quality in the area is a function of both the size of the loading and the size of the area, and would be expected to increase upriver from Conimicut Point to the head of the Seekonk River. Consistent with this idea, the study area was divided into the four sub-areas presented in Figure 3 of Chinman and Nixon (1985). Surface areas and sources are presented in Table 5. Each element receives loads from WWTFs and tributaries discharging to that reach, in addition to the loads to upstream reaches. For example, element 4 in the table receives loads from all sources in elements 1 through 3. The area reported below for element 4 includes the summed areas of elements 1 through 3. Loads entering each area from the Blackstone and Pawtuxet Rivers are quantified as outlined above.

Table 5: Summary of sources and receiving areas

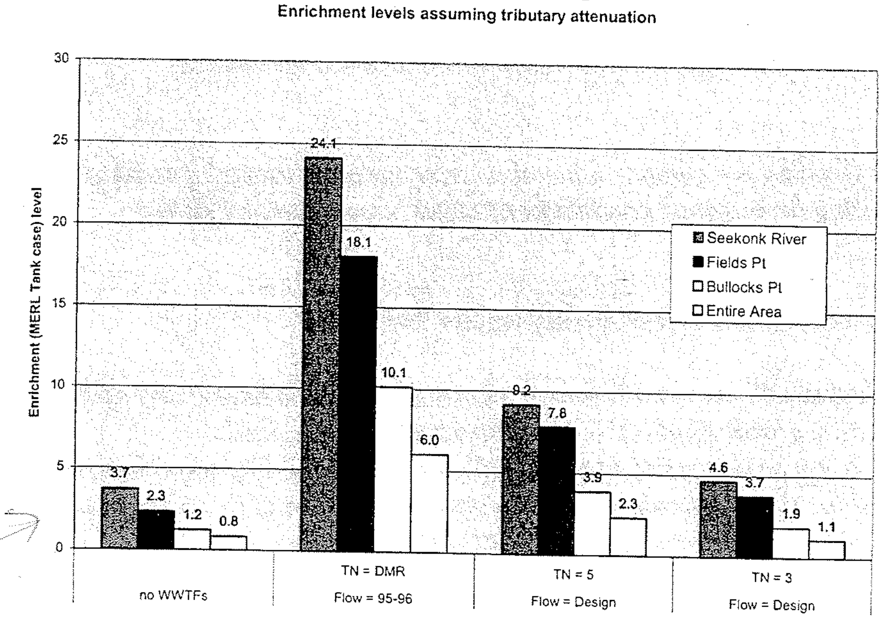
Element Number	Element area (m2)	Sources included: (sources also contribute to downstream elements)
1	2.81E+06	Blackstone River, Bucklin Point WWTF, and Ten Mile River
2	5.81E+06	Fields Point WWTF, Woonasquatucket River, Moshassuck River
3	1.43E+07	Pawtuxet River, East Providence WWTF
4	2.41E+07	Providence and Seekonk Rivers

Results

Figure 19 shows observed or projected loads per unit area for each of the four elements of the Providence River as a function of concentration and flow case (described on the x-axis) for three scenarios. For this example, loads from WWTFs in the tributaries are attenuated prior to reaching the Providence and Seekonk Rivers. The leftmost group of bars represents the projected loading condition of each area with no treatment plants. The remaining groups represent the conditions for the period of 1995-1996, all plants at TN of 5 mg/l and design flows, and all plants at TN of 3 mg/l and design flows.

The figure shows that in the absence of the WWTFs listed in Table 4, loading conditions in the area will range from less that the 1X condition for the area as a whole to slightly less than 4X for the Seekonk river. The second group of bars shows the present loading condition. The following two groups of bars show conditions seen under the TN=5 and TN=3 scenarios and assumed design flow conditions. For the TN=3 case, the loads per unit area drop to under 5x in the Seekonk River and to slightly more than 1X for the area as a whole. Areas north of the Gaspee-Bullock line would receive loads equivalent to the 2X case under this condition. This scenario assumes that some fraction of WWTF loads to tributaries do not reach the

Providence and Seekonk Rivers. For the assumption of no river attenuation, the projected condition of the area is shown in Figure 20. Note that the TN=3 results are identical in Figures 19 and 20 because WWTF loads delivered to the mouths of the rivers dropped below the base load values, hence the base loads were used. As expected, the TN=3 case yield the lowest enrichment scenarios throughout the area. These enrichment levels would be considered to be essentially equivalent to the no-WWTF case. The load per unit area for the TN=5 mg/l case effectively doubles the loading index for each area.



assuming 0.3 mg/l @ mouth flow sampling days

Figure 19: Summary of projected DIN loading rates to selected reaches of the Providence and Seekonk Rivers under four scenarios.

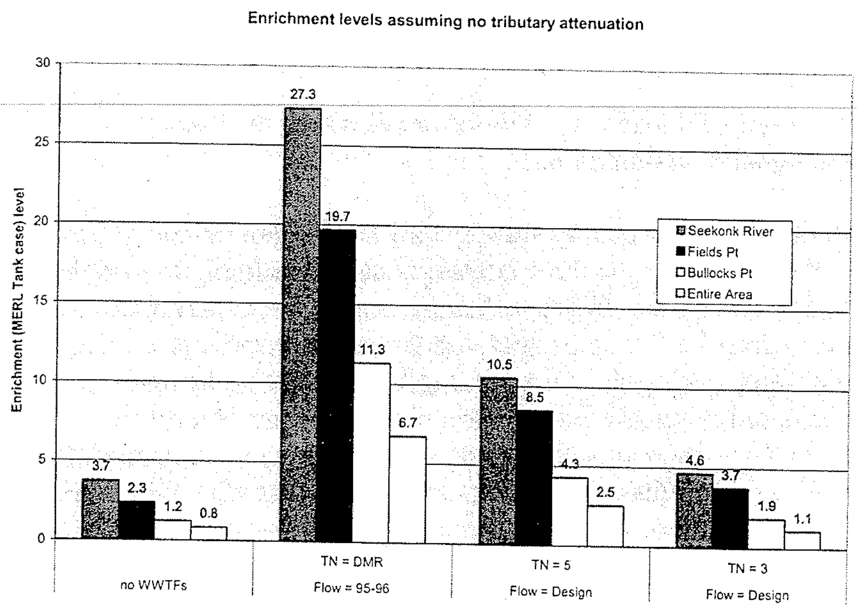


Figure 20: Summary of projected DIN loading rates to selected reaches of the Providence and Seekonk Rivers under four scenarios assuming no uptake of nitrogen along river.

WHAT GOALS SHOULD BE SET FOR THE AREA?

Table 2 in Rule 8.D of the Water Quality regulations (DEM, 1997) lists the dissolved oxygen standard for Rhode Island's Class SB marine waters:

SB waters:
Not less than 5 mg/l at any place or time, except as naturally occurs. Normal seasonal and diurnal variations which result in in situ concentrations above 5.0 mg/l not associated with cultural eutrophication will be maintained in accordance with the Antidegradation Implementation Policy.

Cultural eutrophication is defined as *the human-induced acceleration of primary productivity in a surface waterbody resulting in nuisance conditions of algal blooms and/or dense macrophytes.*

The regulations also contain a definition of low quality waters that states:

"Low quality waters" or "degraded" *means any water whose quality falls below any of the criteria of rule 8.D. in accordance with Applicable Conditions of rule 8.E. and corresponding to its classification as designated in rule 8.C., as determined by the Director, shall be considered degraded for that particular criterion and in violation of its water quality standards and, therefore, unsatisfactory for any designated uses which the Director determines are affected by the particular criterion which is violated. Waters in their natural hydraulic condition may fail to meet their assigned water quality criteria from time to time due to natural causes, without necessitating the modification of assigned water quality standard. Such waters will not be considered to be violating their water quality standards if violations of criteria are due solely to naturally occurring conditions unrelated to human activities.*

Rule 8.E mentioned above defines critical adverse conditions under which the standards apply; Rule 8.C categorizes water quality classifications.

Examination of Figure 4 shows that the water quality standard for DO cannot be met under any loading scenario, because DO minima for the three control tanks (containing un-enriched water from the mouth of Narragansett Bay) are all below 5 mg/L during the experiment. DO minima for the enriched tanks also drop further below the standard as the enrichment level increases. Although the numeric water quality standard of 5 mg/l is not met in the un-enriched tanks, they are not considered to violate the standard because of the "except as naturally occurs" clause in the standard – human activities do not contribute to an exceedence of the standard. The final sentence in the definition of low quality waters clarifies that levels below 5 mg/l are not considered a violation of standards if the violations are due "solely" to conditions "unrelated to human activities". The present regulations coupled with the analysis presented above indicate that, among other reduction actions, WWTF nitrogen contributions must be reduced to the limit of technology in the Providence and Seekonk Rivers.

EPA has issued revised guidance for DO standards in marine waters, and DEM is in the process of implementing the guidance into a revised standard for its marine waters. The revisions have not been finalized, but do allow excursions below a base value of 4.8 mg/l, down to approximately 3 mg/l for short periods of time. Although the new standards have not been established, a review of Figure 4 indicates that it is possible for the standard to be met under some of the lower enrichment cases. The regression equation in Figure 4 indicates that the DO minima for the 2X and 4X cases are 3.7 and 3.0 mg/l respectively. Under these conditions, it is possible for EPA's recommended new DO standard to be met. On the other hand, minima for the 8X and higher cases are less than 2 mg/l. The water quality standard could not be met under any of these conditions. DEM then could not propose loading allocations that were shown to meet the 8X or higher condition if lower levels could be achieved.

Referring back to Figures 19 and 20, one can see even for the projected "no WWTF" loading case, the enrichment status of the Seekonk and upper Providence Rivers varies from a high of 3.7X in the Seekonk River, down to 0.8 for the area as a whole. This "no WWTF" condition defines the best potential condition for the Providence-Seekonk River area. With WWTFs in the watershed reducing their loads to a level consistent with the limit of technology, where effluent TN is 3 mg/l, enrichment levels in the area would range from 1.1X – 4.7X. This scenario is arguably quite similar to the no-WWTF case. For the next higher (TN=5) case, levels in the upper Providence River and Seekonk River increase significantly to 8.0X above Fields Point and to 9.3X in the Seekonk River. These levels would not be acceptable as water quality goals for the area, based on the behavior observed in the MERL experiment.

The allowable plant loads are based on the estimated May – October design flows, and an effluent TN of 3 mg/l, of which 2.0 mg/l is assumed to be refractory (not DIN). These loads are listed by facility in Table 6.

Table 6: Plant TN allocations (at TN=3 mg/l and 90% design flow), and corresponding DIN loads used in this analysis.

Facility Name	TN load at TN=3 mg/l and 90% Design Flow (kg/day)	DIN load at TN=3 mg/l and 90% Design Flow (kg/day)
Cranston	206	69
East Providence	106	35
NBC - Bucklin Point	317	106
NBC Fields Point	664	221
West Warwick	107	36
Warwick	79	26
Woonsocket	164	55
Upper Blackstone, Worcester	572	191
Attleborough	88	29
North Attleborough	47	16

The allowable DIN loads due to WWTFs and river base flow for each reach of the Providence and Seekonk Rivers based on the limit of technology, and not accounting for sources such as stormwater directly discharging to the rivers become:

Element 1, Seekonk River:	526 kg/day
Element 2, Areas north of Fields Point	877 kg/day
Element 3, Areas north of Bullocks Point	1073 kg/day
Element 4, Entire area	1073 kg/day

Experimental data indicate that the 2X and 4X conditions (8.06E-05 kg/m2/day and 1.61E-04 kg/m2/day, respectively) are the likely goal from the perspective of consistency with the State's water quality standards. Specifically, the enrichment status of the Seekonk River would be expected to be consistent with the 4X condition, and the remaining area of the Providence River would be at the 2X or a lower condition. Information from other agencies and researchers indicates that maximizing the area of the Providence and Seekonk Rivers at the 2X level is beneficial from the standpoint of supporting the designated uses of the area for fisheries habitat. The following points underscore this decision:

- Historical data indicate that eelgrass beds were once present in the Providence River, extending northward to Green Jacket Shoal opposite Fox Point (www.edc.uri.edu/ Eelgrass). Eelgrass restoration efforts to date have determined that future restoration efforts north of Prudence Island are water quality limited. The goal of supporting fish and shellfish populations in the Providence River is compatible with the return of eelgrass, at least in the southern reaches of the Providence River and upper Narragansett Bay. Dennison et al. (1993) reported the following habitat criteria for SAV: DIN of 0.15 mg/l (10.7 μM), DIP of 0.33 μM; N:P (atomic) of 32; and chlorophyll *a* of 15 μg/L. The MERL experiment means at the 2X case are 0.26 mg/l for DIN and 12 ug/l for chlorophyll, which compare well with these guidelines.

- Locally, Massachusetts has established environmental general guidelines for total nitrogen concentrations in estuaries. Guidelines began with those developed by the Buzzards Bay Program that rated the condition of a water body based on ambient water quality parameters (Table 7). Each estuary was scored on the basis of a suite of parameters that included mean DIN, Chlorophyll, and DO concentrations. Impaired estuaries received a score of zero if mean DIN levels were greater than 10 uM (0.14 mg/l) or chlorophyll levels exceeded 10 ug/l. The 40% saturation DO levels would correspond to a concentration slightly greater than 3 mg/l in estuarine waters during the summer. Under the Buzzards Bay approach, SB waters would have to meet a score of 40%; SA waters would need to meet 50%.

- Massachusetts has recently refined its approach to incorporate a land-use loading model, and a receiving water quality model that simulates the TN response to loading. The TN target levels (Table 8) are loosely based on the previous Buzzards Bay Program results, but also include site-specific consideration of nitrogen concentrations and indicators of embayment health (dissolved oxygen, phytoplankton densities, water clarity, sediment type and carbon concentrations, macroalgae, eelgrass and benthic communities). Two

Table 7: Buzzards Bay Project Eutrophication Index endpoints

	0 Points:	100 Points:
Summer % Dissolved Oxygen saturation (mean lowest 1/3)	40%	90%
Secchi depth, (m)	0.6	3.0
Dissolved inorganic nitrogen (DIN), (uM)	10.00	1.00
Chlorophyll-a (ug/l)	10.0	3.0
Total organic nitrogen (TON), (mg/l)	0.60	0.28

significant results of the MA work are that mean chlorophyll levels of 10 ug/l and DIN of 10 uM (0.14 mg/l) appear to represent the threshold between suitable and impaired waters. Table 8 summarizes threshold TN concentrations and the resulting observations of embayment health. The 2X case meets the mean chlorophyll a concentration of 10 ug/l (Figure 10) target established by Massachusetts.

Table 8: MA guidelines for TN and environmental health

Condition	Threshold Nitrogen Concentrations	Observations
Excellent	<0.30	
Good	0.30-0.39	Eelgrass beds present, benthic animal diversity and shellfish productivity high, oxygen depletions to <4 mg/L are rare, chlorophyll 3 to 5 ug/L.
Moderate Quality	0.39-0.50	Above this TN range, loss of diverse animal communities and replacement by smaller, shorter-lived animals of intermediate burrowing capabilities, and shellfisheries may shift to more resistant species. Oxygen levels do not generally fall below 4 or 5 mg/L, phytoplankton blooms raise chlorophyll at levels to around 10 ug/L. Macro-algae may be present.
Significant Impairment	0.50-0.70	Large phytoplankton blooms, chlorophyll a of approximately 20 mg/L. Stressful oxygen conditions, major phytoplankton blooms, complete loss of eelgrass, periodic fish kills, macro-algal accumulations and aesthetic (odor) problems are observed. Stress tolerant species persist.
Severe Degradation	>0.70	Complete or near complete loss of oxygen periodically in bottom waters. Macro-algal accumulations and fish kills are observed periodically. Drift algae, lift-off mats and near complete loss of benthic animal communities occurs during a portion of the summer.

Our summary of this analysis is that considerable reductions of existing loads to the Providence and Seekonk Rivers are needed. In the context of existing information on water quality conditions needed to support State water quality standards and the designated uses of the area, a loading scenario consistent with the 2X-4X condition represents the goal for the area. The WWTF scenario that produces loads consistent with this goal would require WWTFs in the watershed to implement reductions to the limit of technology. DEM's interpretation of this limit is the TN=3 scenario, with plant flows at 90% of present design values.

Phased Implementation of Nitrogen Controls

Based upon the MERL enrichment gradient experiment, minimum DO levels of approximately 3.0 and 2.7 mg/l are anticipated from the no treatment plant and LOT cases, respectively. Lower values are expected for the Providence River since it is stratified and the MERL experiment was conducted under unstratified conditions. This analysis indicates that the limit of technology is required but will not fully meet existing water quality standards (minimum of 5.0 mg/l "except as naturally occurs") and may not meet EPA guidelines recently recommended for waters from Cape Cod to Cape Hatteras (EPA 2000). The EPA guidelines allow instantaneous values below 4.8 mg/l provided the cumulative exposure to low DO levels do not exceed the duration criteria established to ensure that the cumulative percentage of larvae affected shall not exceed a 5% reduction in larval recruitment over the recruitment season.

While we believe that the MERL tank results provide an adequate representation of the relationship between nitrogen and oxygen levels in the Providence and Seekonk Rivers, some uncertainty remains regarding predicted water quality improvements and loading reductions necessary to meet water quality standards. As noted above, significantly lower mean DIN concentrations were observed in the Providence and Seekonk Rivers as compared to the MERL experiment for an equivalent loading rate, which may be the result of large differences between the field and experimental flushing times, uptake by macroalgae and denitrification in the bottom waters. Also the MERL experiment DO sampling protocol does not provide sufficient data to fully assess compliance with the recently established EPA guidelines regarding cumulative periods of low dissolved oxygen. However, it is clear that the Providence and Seekonk Rivers are impacted by low dissolved oxygen levels and high phytoplankton levels related to excessive nitrogen loadings. For these reasons, evaluation of phased implementation is indicated. Implementation of a phased approach is consistent with the EPA TMDL guidance (EPA 1991) which states: "For certain non-traditional, problems, if there are not adequate data and predictive tools to characterize and analyze the pollution problem, a phased approach may be necessary."

Evaluation of Implementation Alternatives

For the reasons noted above, RIDEM has evaluated implementation costs, analysis of the performance of available technology, and estimates of water quality improvement to developed a phased plan for implementation of WWTF improvements which maximizes the DO levels relative to implementation cost.

Nine different cases, representing various combinations of nitrogen reduction at 3 MA and 7 RI facilities were examined. The facilities included in this analysis are: Upper Blackstone Water Pollution Abatement District ("UBWPAD" or "UB"), located in Worcester, MA, North Attleboro ("NA"), Attleboro ("A"), Woonsocket ("W"), Bucklin Point ("BP"), Fields Point ("FP"), East Providence, Cranston, West Warwick and Warwick. Estimates were developed for capital costs, including allowances for planning, design, construction and administration, to modify a secondary treatment facility to achieve the target levels on a seasonal basis. Table 9 lists the alternatives evaluated and the estimated implementation costs. Costs shown must be considered "Order-of Magnitude" cost estimates, since specific facility characteristics were not available for many alternatives. The cost are based on estimates which were developed for control of point sources in the Chesapeake Bay watershed (Nutrient Reduction Technology Cost Task Force, 2002), with the exception of a few facilities for which planning estimates or construction bid costs were available. A comparison of the cost to water quality benefits are presented both in terms of the resulting loading gradient (Figure 21) and loading gradient improvement (Figure 22).

Table 9: Estimated cost of WWTF nitrogen reduction alternatives.

WWTF Effluent TN Concentrations (mg/l)	Estimated Cost ($M)
All WWTFs 8 mg/l	104.1
All WWTFs 5 mg/l	192.8
All WWTFs 3 mg/l	337.1
FP, BP 5 mg/l rest 8	120.1
UB, W, FP, BP 5 rest 8 mg/l	156.7
FP, BP 3, UB, W 5 rest 8	212.6
W, FP, BP 5, Rest RI 8, MA - 95-96 levels	85.5
FP, BP, UB, W 5: Rest RI 8: NA, A 95-96 levels	141.1
FP, BP 3, Rest 8	176
FP, BP 3 Rest 5	248.7

As noted in Figures 21 and 22, the following WWTF reductions maximize the water quality improvements relative to costs, 5 mg/l at UBWPAD, Woonsocket, Bucklin Point and Fields Point and 8 mg/l at North Attleboro, Attleboro, East Providence, Cranston, West Warwick and Warwick. Reductions in loading are expressed as the mean 95-96 summer conditions compared to conditions resulting from nitrogen loadings at the target concentrations discharged at summer WWTF design flows (90% of approved design flows). The anticipated loading reduction includes estimates of nitrogen uptake in the tributary rivers (river attenuation). If nitrogen controls are not implemented, loads delivered to the Providence Seekonk system will increase by 55 % as WWTFs increase to their design flows, increasing the existing Seekonk reach loading factor from 24X to 40X. Using the analysis described above, implementation of this first phase would initially reduce the summer season WWTF loading delivered to the Providence Seekonk system by 68% dropping to 52% as WWTF flows increase to their approved design flows. The corresponding Seekonk reach loading factors would drop to 6.6 at current flows and 10X at design flows.

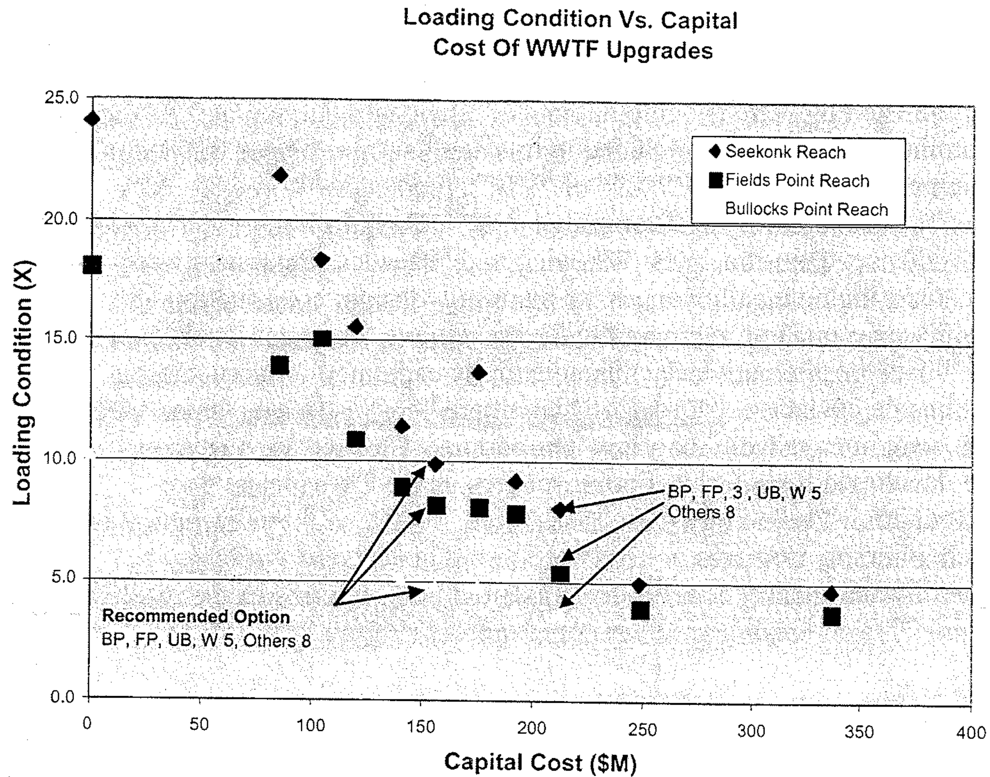


Figure 21: Loading condition versus capital cost of WWTF upgrades

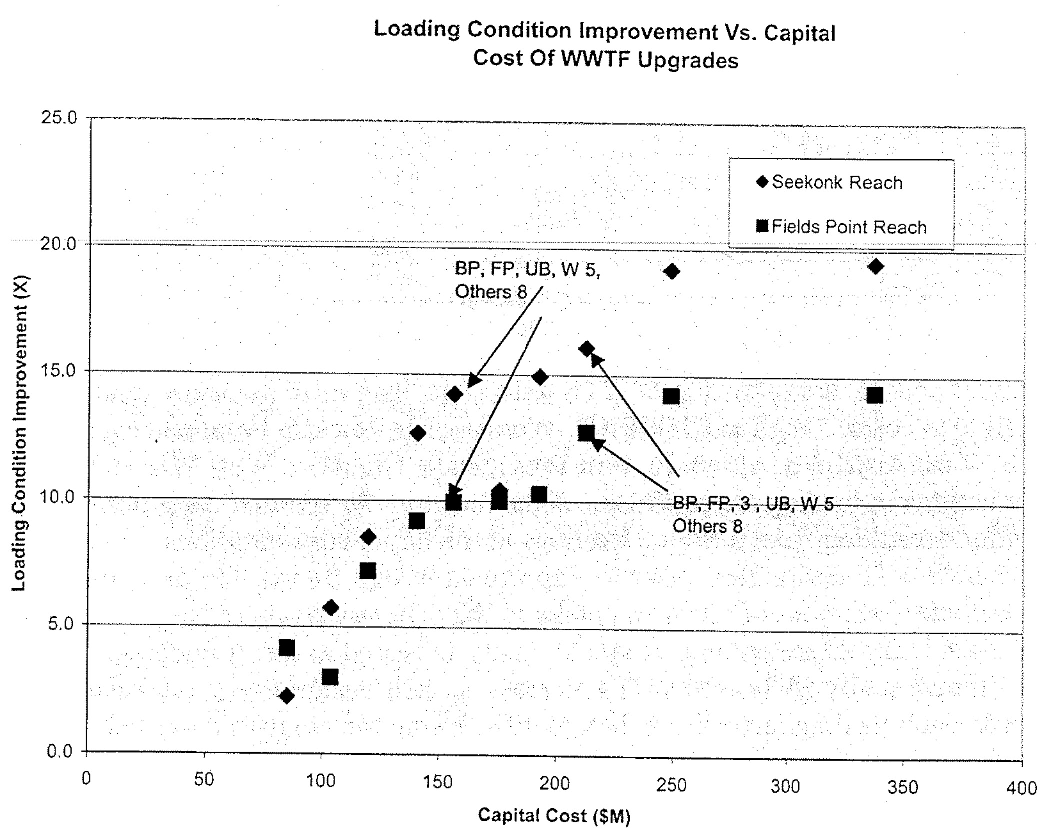


Figure 22: Loading condition improvement versus capital cost of WWTF upgrades.

Evaluation of the Significance of WWTFs in Massachusetts

If the UBWPAD, Attleboro and North Attleboro WWTFs do not implement nitrogen controls, the summer season WWTF loading delivered to the Providence Seekonk River system will decrease from 53% to 30% below current levels. The impact to the Seekonk River is much more significant; a 58% reduction with full participation (the loading factor is reduced from 24X to 10X) but only a 9% reduction (to 22X) if nitrogen loads from these MA facilities are not reduced.

There has been a suggestion that permit limits for nitrogen at MA WWTFs should not be pursued until after current upgrades are completed and further information is available to evaluate river attenuation (e.g. a river delivery factor of 85% was computed for the Blackstone River). DEM does not believe this is appropriate, since river delivery factors would have to be 17% and 7% before the UBWPAD at 95-96 concentrations and design flow would be reduced to the loading resulting from the 5 mg/l discharge proposed for Bucklin Point and Woonsocket WWTFs and at their design flows. The UBWPAD design flow is large relative to the other WWTFs impacting the Seekonk River: 1.8 times larger than Bucklin Point and 3.5 times larger than Woonsocket. Furthermore, the UBWPAD is currently planning an upgrade and it would be prudent to consider nitrogen removal options while the planning process is underway. UBWPAD, North Attleboro and Attleboro WWTFs play a significant role in the ability to improve water quality in the Providence and Seekonk River system, and efforts to reduce their nitrogen inputs should be initiated as soon as possible. RIDEM will be working with Massachusetts and the US EPA to pursue nitrogen reductions at these facilities.

Implementation of Nitrogen Reductions

As noted earlier, MERL tank experiments suggest that LOT treatment is required to meet water quality standards. However, based on a comparison of technology, costs and reductions in the nutrient loading factors for the Providence and Seekonk River Systems, RIDEM has established a phased reduction strategy. The first phase is based on achieving the following WWTF effluent concentrations: 5 mg/l at UBWPAD, Woonsocket, Bucklin Point and Fields Point and 8 mg/l at North Attleboro, Attleboro, East Providence, Cranston, West Warwick and Warwick. This analysis acknowledges that loadings will increase as WWTF flows increase to their design flows, but follow-up monitoring and possibly water quality modeling will be needed to determine whether additional reductions are required. Because LOT treatment is presently indicated, it is DEM's position that it is appropriate to express WWTF permit requirements as a concentration limit, which will enhance the near-term environmental improvement while plants are below their design flows.

The analysis presented herein evaluates the impact of current and future nitrogen loading scenarios on the Providence and Seekonk Rivers using the inputs from the most significant WWTFs. For example, summer loads measured at the mouth of Blackstone River were expressed as loading from the Woonsocket and UBWPAD WWTF inputs, attenuated to match loads measured in the river. UBWPAD is by far the single largest WWTF in the

Blackstone River Watershed. Attenuation from the state line to the mouth of the Blackstone River was established based on the following assumptions: that majority of the loadings during the 95-96 study period were from the most significant point sources (Woonsocket and UBWPAD), that Woonsocket is located close to the state line, that the load crossing the state line and Woonsocket's loading are equally attenuated and adequately represented by a single delivery factor. The first phase results in a **DIN** load at the mouth of the River of 403 kg/day or 463 kg/day combined input from Woonsocket and MA sources. Of this allowable load, 85 kg/day has been allocated to Woonsocket and 378 kg/day to MA sources.
Upper Narragansett Bay

Areas of Upper Narragansett Bay are affected by the WWTFs that impact the Providence and Seekonk River Systems. In addition, to reduce its impact on Greenwich Cove, the East Greenwich WWTF is in the process of constructing modifications to achieve a seasonal nitrogen limit of 5 mg/l as required by its RIPDES permit. It is DEM's position that the point source discharges to the Warren River will also need to reduce nitrogen to address impacts to the Palmer River.

Implementation of nitrogen removal would initially reduce the summer season nitrogen load discharged from these eleven Rhode Island WWTFs to the Upper Bay by 65%, dropping to 48% as WWTF flows increase to their approved design flows.

Monitoring Water Quality Improvements

An integral component of this phased implementation approach is adequate monitoring and assessment of water quality changes to determine if additional reductions are necessary to meet water quality standards. Of particular concern are the establishment, maintenance and data processing for a system of continuous dissolved oxygen, chlorophyll, temperature and salinity monitors strategically located throughout the Bay. DEM, in partnership with NERRS, the Narragansett Bay Commission, University of Rhode Island and Roger Williams University increased the Narragansett Bay continuous water quality monitoring system from 7 to 9 stations during the summer of 2004. DEM has obtained funding from the federal Bay Window grant to increase the number of stations to at least13 by the summer of 2005. This monitoring network will provide the data necessary to evaluate compliance with water quality standards, particularly temporal detail needed to evaluate compliance with EPA's dissolved oxygen guidelines. The United States Environmental Protection Agency (EPA), Office of Water's, Office of Science and Technology EPA is currently seeking a contractor to assist DEM with the development of methods to review continuous time series DO measurements for compliance with EPA's October 2000 recommended ambient water quality criteria. The contractor will also assess monthly transect surveys of the bay to determine whether modifications are needed to the existing and planned monitoring network based and provide technical support to establish guidelines for evaluating the response to changes in nitrogen loads .

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