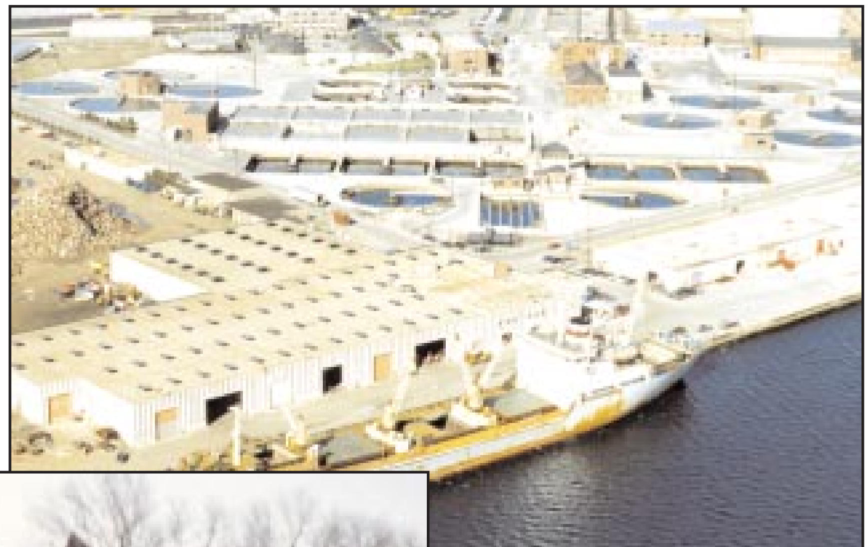
Nutrients and Narragansett Bay

A Workshop on Nutrient Removal for Wastewater Treatment Facilities

Proceedings



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Coastal Resources Center
University of Rhode Island

Nutrients and Narragansett Bay:

Proceedings of a Workshop on Nutrient Removal for Wastewater Treatment Facilities

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Introduction

A workshop to present ideas and technologies for nutrient removal for wastewater treatment facilities (WWTFs) that discharge to Narragansett Bay and tributaries was hosted by Rhode Island Sea Grant and the Rhode Island Department of Environmental Management Narragansett Bay Estuary Program in September 1998. Town managers or finance directors and treatment facility operators from every municipality in Rhode Island as well as staff from key state agencies and the Rhode Island legislature attended the event. Following presentations summarizing nutrient loading to the bay and probable effects, experts from around the country presented successful nitrogen removal case studies. Experts on costs and effectiveness of denitrification technologies gave presentations and participated in working sessions. Discussion sessions were held to determine monitoring needs and funding strategies for implementing denitrification technologies in Rhode Island sewage treatment facilities. These presentations are summarized in these proceedings.

Workshop Recommendations

Strategic Implementation of Nutrient Removal from Publicly Owned Sewage Treatment Facilities

- Rhode Island sewage treatment plants willing to proceed with denitrification should be encouraged to do so. In Connecticut, nitrogen loads to Long Island Sound were limited to current levels while more studies were conducted to support additional removal. Other states have encouraged dischargers to set their own limits based on expected treatment plant performance.

- Rhode Island should provide incentives for wastewater facilities to experiment with denitrification technology. Experience in other states has shown that the differences in wastewater characteristics, facility structures, and the interest of plant operators in using new technology will determine where the experimentation will occur. Site-specific experimentation is cost-effective and provides an opportunity for cultivating collegial relationships between regulators and the treatment plant operators.

- Rhode Island Department of Environmental Management (RI DEM) should rethink how the Rhode Island Pollutant Discharge Elimination System (RIPDES) permits are written for plants trying biological nutrient removal (BNR). BNR produces variable discharge characteristics, with worst months as much as 40 percent above the average. Permits written with an annual average limit rather than a monthly average would allow for this variability and encourage BNR application.

- Many treatment plants do not have the in-house monitoring capability needed for managing BNR systems. Rhode Island could establish a regional laboratory to assist treatment plants with analyses needed for monitoring BNR systems.

Funding

The state of Rhode Island has reached its limit in bonding. Municipalities are fiscally constrained. Creative ways to leverage funds must be identified in order to pay for adapting sewage treatment plants for nutrient removal.

- The State Revolving Fund (SRF) has money that could be used for BNR. Rhode Island should look into whether the SRF equations for calculating payback rates could be changed to encourage BNR experimentation.

- Rhode Island is going to receive additional Clean Water Act Section 319 funds. The Environmental Protection Agency (EPA) could be more flexible in its requirements for match to encourage BNR.

- If Rhode Island Aquafund is reauthorized in 2000, those bond funds may be available for planning and construction of nutrient removal processes for sewage treatment facilities.

- Connecticut instituted a competitive bidding process for the lowest cost treatment per pound of nitrogen removed. Because BNR uses less power than chemical treatment power companies supplemented with matching money, Rhode Island should consider adopting Connecticut’s approach of obtaining federal grant money to initiate BNR treatment.

- In the Chesapeake Bay region, a panel of legislators meets monthly to discuss emerging environmental issues facing the bay. These meetings keep the political leadership abreast of environmental needs, including the need for funding for new initiatives like reducing nutrient loading to the bay. This might be worth considering for Rhode Island.

Monitoring

- More monitoring is needed to fully understand hypoxia and its linkages to nitrogen loadings to Narragansett Bay.

- A modeling framework for synthesizing data needs to be finalized.

Building Public Support

- In Connecticut and the Chesapeake Bay region, the public was aware of the linkages between degraded bay water quality and nutrients in point source discharges before efforts were made to implement BNR. The Rhode Island public has not been similarly educated. Rhode Island needs to develop a public information strategy to inform people about bay issues and initiatives to address them. It is important to include a wide range of interest groups — legislators, businesses, recreational users, government agencies (local, state, federal), etc.— in the development and implementation of this strategy to build awareness and support of reducing pollutant loadings to Narragansett Bay.

Nutrient Loadings to Narragansett Bay

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Introduction

This presentation summarizes current information on the annual inputs and outputs of organic carbon, nitrogen, and phosphorus to Narragansett Bay. For the purpose of this analysis, I have defined Narragansett Bay to include Narragansett Bay proper (the East and West passages from the mouth to Conimicut Point, including side bays and harbors), the Providence and Seekonk River estuary, and Mt. Hope Bay and the Taunton River estuary. The Sakonnet River, which has very restricted hydraulic connection with the rest of the bay, is excluded. Narragansett Bay has a water area of 328 km^2 with a mean depth of 8.6 m. The average total fresh water input to the bay is about 105 $m^3\ s^{-1}$.

Important Sources of Nutrient Loading

Sewage discharged from treatment plants directly to the bay amounts to over a quarter of the total nitrogen loading to Narragansett Bay (see input section of nitrogen mass balance table). Three facilities account for 85 percent of that loading: the Narragansett Bay Commission facilities at Field's Point and Bucklin Point and the East Providence Plant. Denitrification technologies installed at these three plants would have the greatest impact on loading reduction depending on the effectiveness of the nitrogen removal systems.

Twenty-two sewage treatment plants discharge into rivers that flow into Narragansett Bay. Their loading is included in the summary of rivers inputs in the table of nitrogen mass balance for Narragansett Bay. Rivers, with loadings from sewage treatment plants that discharge to them, account for approximately two thirds of the total nitrogen loading to Narragansett Bay.

Data Sources

The following table summarizes pertinent information about data used to complete this analysis. Complete references can be found in S.W. Nixon, S.L. Granger, B.L. Nowicki (1995) An assessment of the annual mass balance of carbon, nitrogen, and phosphorus in Narragansett Bay. *Biogeochemistry* 31: 15-61.

Rivers were sampled every two weeks for a year, which captured some of the higher discharges associated with winter storms. Within the range of discharge conditions measured, there was excellent correlation between river flow and nutrient flux for some constituents (dissolved organic carbon, particulate organic carbon) but not for others (dissolved inorganic phosphorus, particulate phosphorus, total phosphorus), so it was impossible to use a rating curve approach. We therefore chose to use Beale's flow-weighted unbiased estimate to calculate annual fluxes from the biweekly concentration measurements and daily flow data collected during one calendar year of measurement.

Sources	**Type of Nutrient**	**Station locations**	**Date of Study**
Atmospheric deposition	Phosphorus	URI, GSO	1975
	Nitrate, ammonia	Prudence Island	1989, 1990
	Dissolved organic nitrogen (DON), nitrate	URI, GSO	1985, 1986
River	Dissolved and particulate carbon, reactive phosphate, dissolved organic phosphorus (DOP), particulate phosphorus, ammonium, nitrite, nitrate, DON, particulate organic nitrogen	Blackstone, Pawtuxet, Moshassuck, Woonasquatucket Rivers	1982, 1983
		Taunton	1988, 1989
Urban storm water runoff	Dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP)		1979, 1980
Sewage treatment plants	Dissolved and particulate carbon, reactive phosphate, DOP, particulate phosphorus, ammonium, nitrite, nitrate, DON, particulate organic nitrogen	Bucklin Point & Wastewater Treatment Plant, Narragansett Bay Commission Fields Point, East Providence	1983
	Total nitrogen, total phosphorus	East Greenwich, Quonset, Warren, Bristol, Jamestown, Newport, Fall River	1985-1986

There are 32 sewage treatment facilities that discharge domestic and industrial wastewater within the Narragansett Bay drainage basin. Twenty-two sewage treatment plants release their effluents into rivers and streams, and their contribution to the bay is included in the rivers loading estimates of carbon, nitrogen, and phosphorus. Nine of the remaining plants discharge directly into the tidal waters of the Seekonk-Providence River estuary or into Narragansett Bay proper, and one discharges into Mt. Hope Bay. Biweekly grab samples of final effluent from each of the three largest treatment plants that discharge directly to the Seekonk-Providence River estuary were collected during 1983. The volume of effluent discharged each day was reported by the treatment plants and we calculated annual nutrient fluxes using Beale's unbiased estimation technique. These effluents account for 85 percent of the average daily direct discharge of sewage to Narragansett Bay. The remaining six treatment plant effluents were sampled three or four times during 1985 and 1986. The daily fluxes for each of these plants were then calculated and multiplied by 365.

Annual Budgets

The following tables summarize our current assessment of the annual mass balance of nitrogen, phosphorus, and organic carbon in Narragansett Bay. Units are 10^6 moles yr^{-1}.

Nitrogen	NO2 +NO3	NH4	DIN	DON	PN	Total
Inputs						
Atmospheric deposition	19	5.6	24	5.6	-	30
Rivers and streams	177	113	290	96	12	400
Urban runoff	~4	~13	17	18	2	37
Sewage treatment plants	6.2	136	142	30	10	183
	206	268	473	150	24	650
Outputs						
Export to offshore	?	?	?	?	?	?
Denitrification						85-170
Hard clam harvest						3.4
						>88-173
Changes in storage						
Accumulation in sediments						44-97

Phosphorus	DIP	DOP	PP	Total
Inputs				
Atmospheric deposition	-	-	-	0.13
Rivers and streams	13	3.2	4.8	21
Urban runoff	2	0.8	1.2	4
Sewage treatment plants	9	2.8	1.9	14
	24	6.8	7.9	39
Outputs				
Export to offshore	?		?	?
Hard clam harvest				0.2
Changes in storage				
Accumulation in sediments				5-8

Organic Carbon	DOC	POC	Total
Inputs			
Rivers and streams	1440	375	1815
Sewage treatment plants (STP)	190	140	330
STPs corrected for malfunction of Fields Point	190	45	235
Primary production	?	9600	9600
Outputs			
Export to offshore	?	?	?
Hard clam harvest	-	7-14	7-14
Total system respiration (CO2)			?
Changes in storage			
Accumulation in sediments	-	575-880	575-880

Conclusions

The largest part of each of these biologically important elements enters Narragansett Bay in inorganic form. Even in this system with an urban shoreline and a densely developed watershed, organic carbon fluxes from land amounted to only some 20 percent of primary production. An unknown fraction of the primary production is supported by anthropogenic nutrient enrichment. Biological fixation of inorganic carbon in the bay is sufficiently large that it can not be sustained by the inputs of nitrogen and phosphorus alone, even if the organic forms of nitrogen and phosphorus are considered. Nutrient regeneration is important to maintaining the productivity of the system.

The amount of nitrogen entering Narragansett Bay from upstream land drainage and sewage is about 2.5 times greater than the amount from direct sewage discharges. Direct deposition of nitrogen from the atmosphere (including all forms of nitrogen) provided only about 4 percent of the total nitrogen input, but the relative contribution of atmospheric deposition, sewage, and fertilizer to the nitrogen burden of the rivers is not known. The amount of nitrogen entering the bay from land drainage appears to vary by a factor of two between dry and wet years, thus indicating the importance of nonpoint sources of this nutrient. Landward flowing bottom water from offshore may provide a flux of DIN equal to 15 to 20 percent of the total nitrogen input from other sources.

The flux of DIP from offshore Narragansett Bay appears to be approximately the same as the flux from land drainage and upstream sewage and fertilizer. Direct sewage discharges to the bay provide about 20 percent of the total phosphorus input. The input of DIP varies little between wet and dry years, reflecting the importance of point sources for this nutrient.

Sediment deposition rates over most of Narragansett Bay appear to be low, and only a small fraction of the organic matter formed in the bay is buried. Because the bay is shallow, a significant amount of the fixed organic matter is decomposed in anoxic bottom sediments, thus allowing denitrifying bacteria to remove 10 to 25 percent of the total nitrogen input to the system.

The greatest share of the organic matter formed in the bay is consumed within the system and primarily within the water column. Because of this, almost all of the nitrogen and phosphorus that enters the bay in inorganic form is finally exported in inorganic form to the waters offshore. On average, the anthropogenically generated nutrients that enter Narragansett Bay from land and atmosphere do not remain for long and there is little record of their passing. During the time they are in the bay, however, their impact on the biology of the system may be profound.

Nutrient Impacts and Signs of Problems in Narragansett Bay

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Introduction

In dealing with environmental pollution, we can talk of many potential threats to the health of Narragansett Bay. For over two decades, WWTFs and state environmental agencies have engaged in serious efforts to deal with many of these threats, decreasing the level of impact from pollutants like heavy metals through highly successful programs such as industrial pretreatment and toxic source reduction. Perhaps because of this success with toxics, I have slowly come to conclude that excess nutrients and the resultant production of massive amounts of plant life (sometimes termed eutrophication) to levels that exceed the recycling capacity of the estuary are the sources of some of the most widespread and serious pollutant impacts still occurring in Narragansett Bay.

Nutrient Impacts

I present a brief list (Table 1) of some of the impacts scientists have seen associated with excess nutrients, but due to time constraints, I will have to focus on a very small subset of these. Some of these impacts are still poorly understood and are therefore difficult if not impossible for us to predict in terms of mathematical relationships to nutrient loads. Often, we only learn of the response once observable widespread negative changes appear in coastal ecosystems where excess nutrient loadings continue to slowly increase.

Because the greatest nutrient loads to Narragansett Bay take place in the urbanized upper bay, the primary causes of the degraded ecosystem responses observed there are often difficult to separate. Highly contaminated sediments, toxics in point source effluents, stormwater carrying petroleum hydrocarbons, polycyclic aromatic hydrocarbons, and heavy metals have all been argued at one time or another to be the most significant source of all our urban estuary's woes. In the past, these toxins entered the ecosystem in very high levels, and possibly caused negative impacts, especially in the urbanized waterways. However, loadings of most toxics have decreased, even in the urban areas, and most of these toxics are not readily bioavailable except perhaps in "hot spots." Over my 24 years of experience in the field of marine environmental pollution, I have become increasingly convinced that much more widespread impacts within the upper bay and poorly flushed coves and harbors come from excess nutrient loadings, especially excess nitrogen loads.

Nitrogen, especially inorganic forms like ammonia and nitrate, is the excess nutrient that is prevalent in Narragansett Bay. With the addition of excess nitrogen, tiny one-celled plants in the water (algae or phytoplankton) bloom in huge numbers, coloring the water and decreasing its clarity. This immediate response causes problems for plant species that live on the bottom and need fairly high light levels. And so the first sign of trouble tends to be the disappearance of seagrasses like eelgrass (*Zostera marina*), a species considered to be critical habitat for the young of many marine organisms such as crabs, shrimp, scallops, and fish.

Problems in Narragansett Bay

Here in Rhode Island, researchers have shown declines of over 40 percent in eelgrass beds in the south shore coastal ponds associated with increased nitrogen loads due to septic system/housing density within the watersheds (Short *et al*. 1966). In Narragansett Bay, work initiated by the RI DEM Narragansett Bay Estuary Program (Doherty 1997) and continued by research scientists at URI has shown that areas of the upper bay, especially Greenwich Bay, Potowomut River, parts of the Providence River, and the Palmer River, appear to have been covered once by extensive eelgrass beds (Kopp *et al*. 1997). All disappeared by the 1950s or 1960s, with the majority of eelgrass in the bay today occurring near the southern end of Prudence Island and around Jamestown and Newport (Narragansett Bay Estuary Program Critical Habitat Map, 1998). Although disease and hurricanes played a role, the inability of eelgrass to maintain itself today in the upper half of the bay strongly points to excess nitrogen.

Beyond water clarity, there is another impact—the decay of the huge blooms of algae once they die and sink to the bottom. Bacteria perform this decomposition and use up oxygen in the bottom waters to accomplish their role. If physical conditions set up a layering or stratification of the water column so that the bottom waters cannot mix with surface waters, there is an inevitable drop in oxygen levels to hypoxia ($\leq$2 ppm dissolved oxygen (DO)—normal in the bay is ~ 6 to 9 ppm) or even anoxia (no oxygen in the water). Bottom organisms are in real trouble at that point. Wherever this mass of poorly oxygenated bottom water moves up or down the bay, as long as it stays relatively unmixed, it acts like a "cloud of death" to any slow-moving or immobile organisms in its path. Effects of different low DO concentrations are listed in Table 2.

Of all the excess nutrient impacts, I find this impact to be the premier negative consequence of excess nitrogen to the bay. To understand the profound consequence of even rare events of low DO on bay life, you need only consider which threat would be greater to you: a lunch of striped bass with its associated slight increase in unknown health risks (cancer? hormone mimic effects?) due to a small incremental increase in PCBs in your fat tissues, or remaining chained to a chair in a room while all the oxygen in sucked out over a 2 to 3 hour period! I assure you that the choice to take the striped bass meal and leave the room is the correct one. As the American Lung Association motto declares: "When you can't breathe, nothing else matters!"

In preparing for this talk, I have come to learn that I am not alone in this view that hypoxia/anoxia subjects estuaries to widespread long-term consequences wherever it occurs. Dr. Robert Diaz of the Virginia Institute of Marine Science recently reported, "Oxygen deficiency may very well be the most widespread anthropogenically induced deleterious effect in the marine environment that causes localized mortality of benthic macrofauna" (Diaz and Rosenberg 1995). Diaz further reported, "No other environmental variable of such ecological importance to coastal marine ecosystems around the world has changed so drastically in such a short period as DO. While hypoxic and anoxic environments have existed through geological time, their occurrence in shallow coastal and estuarine areas appears to be increasing, most likely accelerated by human activities" (Diaz 1995).

Why haven't we seen banner headlines about such a problem in parts of Narragansett Bay? One would think that such a serious impact would reach the front pages of the news and be at the forefront of environmental concerns for both the public and the environmental agencies. Yet it is not. Partly, it is because the main impact is on the bottom waters, so the most serious biological consequence—widespread "kills" of mainly bottom organisms—will remain unseen to most of us. I should note here that the most important commercial bottom organism, the adult quahog or hard shelled clam, is practically immune from hypoxic impacts (it is a world champion in "holding its breath") so its continued presence does not vouch for other bottom organisms' continued existence. Fish kills sometimes do hit the news, but they can be due to different causes and only occur from hypoxia under special circumstances when upwelling or other unusual meteorologically driven events trap fish in low-oxygen shallow waters. Fish are usually able to avoid the "kill zones."

A second reason for the lack of recognition of such events is due to the rarity and brevity of meteorological conditions likely necessary to cause hypoxia beyond the Providence/Seekonk River ship channel. Most of the bay below Conimicut Point is usually well mixed and therefore usually has adequate DO at all depths. Specific physical conditions are thought to be required to form hypoxia in the upper bay (Table 3). The extent and severity of hypoxic events are linked to year-to-year variability in weather. They are likely to be most serious in years with particularly wet springs and early summer storms followed by very hot weather and calm wind, so hypoxic events will tend to be rare and short-lived (on the order of hours or days). The odds of sporadically monitoring DO in the bay at the same time that such a short-term event is occurring are low. Unfortunately, such rare short-lived acute events can have profound long-term impacts on life at the bottom of the bay.

The deep waters of the Providence River ship channel experience very low oxygen levels down to hypoxic and even anoxic DO levels every year from mid-June through mid-September (Turner 1997), but this area has always been considered extremely degraded, with only the hardiest of bottom organisms remaining, so few tend to be concerned by loss of what is already considered a very degraded benthic community. No state monitoring programs measure DO beyond the Providence River on a regular basis at this time. We are presently ignorant of the extent and frequency of occurrence of low DO events below this point.

I believe we have become overly complacent in assuming that low DO does not occur in open waters of the bay below Conimicut Point. Some researchers have pointed out that the incidence of anoxia and hypoxia is likely seriously underestimated in all but extremely degraded systems, due to its rare and fleeting occurrence (Summers *et al.* 1997).

In the upper bay and other areas of the bay, circumstantial evidence as well as occasional (but rare) data of bottom summer DO levels strongly suggests that occasional severe hypoxia does in fact occur well below Conimicut Point. The frequency of occurrence is anybody's guess, although I suspect it occurs for short periods of 1 to 2 days duration approximately every 2 years or less in the upper bay, Greenwich Bay, Mount Hope Bay and perhaps the Palmer and

Potowomut Rivers, based on fish kills, bottom opportunistic communities and other circumstantial evidence.

The conditions necessary to stratify the water are detailed in Table 3. As noted, if hypoxia sets up in the bottom waters, followed by steady winds, upwelling of these low-oxygen bottom waters towards the shallows may occur, and fish may become trapped, potentially resulting in a fish kill. Such kills would be expected to include multiple species, and would also likely include crabs and sand shrimp. This situation would most often occur on the western shores of the bay since winds are usually out of the west-southwest in the critical summer months.

There is also a possibility that more localized shallow water hypoxia may occur in coves and small embayments, where the nuisance shallow water summer seaweed called "sea lettuce" (*Ulva lactuca*) often grows in significant amounts due to high nutrient levels. This plant biomass may begin to deteriorate rapidly in late summer due to warm water temperature limits (~25^{o} C). If this occurs at the same time that all mixing energies are at a minimum (calm winds, neap tides), especially if calm but cloudy weather sets in, then pockets of hypoxia or even anoxia may develop overnight. More work needs to be done to investigate this issue.

The actual response of bottom organisms depends on a species' sensitivity to low oxygen. These responses have been well described in the literature (Baden *et al*. 1990, Burnett 1977, Diaz and Rosenberg 1995, Harper and Rabalais 1995, Johansson 1997, Swanson and Sindermann 1979). Highly mobile organisms like fish and squid will usually leave an area once DO levels reach 2.5 to 2 ppm. At this point, some bottom-digging organisms may begin to emerge from their burrows. As DO levels continue to decline, more animals that live in the sediments begin to emerge, exhibiting odd behaviors, like crabs and lobsters standing on "tiptoe" and crawling to the highest points on the bottom, since all are seeking places with more oxygen. In fact, one of the difficulties in recording hypoxic events is that the critical area for DO measurements as far as bottom organisms are concerned is the sediment/water interface. Unfortunately, most DO measuring devices are set in the water column at 0.5 to 1 m *above* the sediments, an environment that is likely to show higher DO levels than those the benthic organisms are actually experiencing.

An interesting result of this low-oxygen emergent behavior is that bottom trawls may actually show an *increase* in bottom organisms captured at this point (Baden *et al.* 1990). However, the end is in sight for these organisms. Once DO reaches $\leq$ 0.5 ppm, most are dead.

In Narragansett Bay, the most sensitive species are likely to be benthic crustaceans such as lobsters, crabs, sand shrimp, and mantis shrimp, as well as starfish and sea urchins (Table 4). Most shellfish are fairly resistant, especially the quahog, although anoxic events have caused mass mortality of softshell clams off New Jersey (Swanson and Sindermann 1979). Scallops are likely not as resistant and are therefore likely to be victims. However, scallops are no longer a significant resource in the bay due to unexplained losses since the 1950s and 1960s. I do not know the sensitivity of marine whelks, but they are likely less resistant than the clams. The young-of-year winter flounder may be at significant risk when upwelling events occur, since these are often observed in large numbers as victims of shallow water multispecies fish kills due to low DO and recorded in the RI DEM 305(b) reports from 1986 to 1997.

Diaz and Rosenberg (1995) have indicated that estuaries around the world are experiencing increased incidence of hypoxia and anoxia, due to increased nutrient loads from human-linked activities. They argue that a progressive pattern of four stages to degradation has been seen across all estuaries, dependent on the frequency and extent of hypoxic/anoxic events (see Table 5). If hypoxia is rare in an area and occurs for only a day or so on a frequency of less than once every four years or so, the bottom community can usually return to normal. However, if the occurrence is every two years, Diaz and Rosenberg state that no system to date has been capable of returning to the original benthic community. Instead, a new community of opportunistic benthic species replaces the old one. This community is considered to be less diverse, usually made up of lower numbers of small, short-lived opportunistic species (Table 4) like certain small marine worms (*Mediomastus ambiseta*) and clams (*Nucula annulata*). Much of the upper bay and an area north of Jamestown appears to have shifted to just such an opportunistic community around 1975, and this is now the normal community in these areas (Frithsen 1990).

If the hypoxia occurs yearly, then the system becomes a pulsed system, with no organisms living an entire normal lifetime. Instead, opportunists have a one-year "death sentence" imposed on them, and bacteria take over the bottom during the summer anoxic period. As waters cool and oxygen returns to safe levels, the young of the opportunistic species, normally found in the water column plankton, drop down and begin the short annual cycle of life and death once again. Such a condition appears to be the norm at this time in the Providence/Seekonk River ship channel.

One speculation many have had concerning excess nutrients is that the algal blooms should provide more food to the system, eventually increasing the amount of fish life. In fact, such increases in fish populations have been seen in some systems, but like the old saying "watch what you wish for," the actual result is not always wanted or expected. Some have noted that the actual response may depend on whether hypoxia sets in or not. Once hypoxia becomes part of the system response to the nutrients, the young of demersal (bottom) fish populations like flounder species often decrease and are replaced by water column herbivore fish species like anchovies and herring (Table 4. Breitberg 1997, Boesch 1995, Hanifen *et al*. 1995). Unfortunately for commercial fishermen, the latter fish are usually of much lower value than the flatfish.

Although we do not have an adequate handle on DO levels in the bay throughout the critical summer months, and therefore do not really know how often and over what extent hypoxia can set in over the bay beyond the Providence River, I have attempted to develop an educated guess. I have taken all DO data I was able to gather from both state agency and university research contacts for the period from 1986 to present, as well as information on anoxic sediments, REMOTS data (camera photos of various areas of the bay bottom analyzed for dominance of "opportunistic" species) and Redox Potential Discontinuity depths (a measure of how deep oxygen gets down into the top layer of the sediments) (Vallente *et al*. 1992), a Narragansett Bay Project report summarizing almost 40 years of available benthic community data (Frithsen 1990), and all DO-related fish kills reported in the RI DEM Biennial 305(b) Reports from 1986 to 1997. Table 6 lists the data sources/references used. From this information, I developed a map of occurrences (see Figure 1), and then transformed this using best professional judgement into a "hypoxia risk" map (Figure 2).

Although the frequency of hypoxia is still unknown for all but the Providence River, where it appears to be an annual event, the fish kill data suggest that upwelling or shallow water hypoxic events kill fish in parts of the upper bay approximately every two years. Severe hypoxia has been recorded at least once (late June 1998) as far south as the Upper West Passage (just north of Allens Harbor, C. Strobel, US EPA, personal communication), with classic symptoms of bottom trawl catches over several days showing a sudden and complete absence of fish in a formerly good bottom fishing area, dead mantis shrimp (*Squilla empusa*), and bottom oxygen (~10 m depth) at ~ 1.0 ppm. Since this event is likely linked to record-breaking mid-June rainfall in Rhode Island, it is unclear how often this area experiences such events. It should be kept in mind that this area is just north of the Frithsen post-1975 degraded mid-bay bottom station (Frithsen 1990).

Overall, the upper half of the bay north of Jamestown seems at greatest risk, with a possible increased risk to the Upper West Passage (although the lack of data in the deep Upper East Passage may be biasing this view). Large multispecies fish kills are likely to be a conservative "lowball" estimate since we are actually missing benthic kills because fish are able to avoid the area.

Based on this information, I believe it is likely that hypoxia may be occurring at the surprisingly common rate of at least one event/summer in significant parts of the upper bay, Greenwich Bay, Mount Hope Bay, and Potters Cove (Prudence Island) for short periods of 1 to 2 days. Based on continuous DO data for 1996 and 1997, Apponaug and Greenwich coves in Greenwich Bay seem to be experiencing annual seasonal anoxia throughout June, July, and August. DO in these coves is characterized by wild swings from daytime supersaturation to evening anoxia, likely linked to photosynthesis and respiration activities of the tremendous layers of sea lettuce (*Ulva*) carpeting the coves (Spaulding *et al*. 1998).

Anoxic or hypoxic conditions may occur in the open waters of the Upper West Passage during summers when extensive stratification sets in, a situation that is likely to occur less often than in other parts of the bay. It would be useful to look at continuous monitoring data from Dana Kester, URI Graduate School of Oceanography, for his Hope Island station in this area to approximate low DO frequencies as well as gather density data to project the frequency of stratification events which could potentially cause hypoxia to continue this far down the bay.

The East Passage is poorly known in terms of DO regimes during this critical summer period, but very sporadic incidences of blue mussel mass mortality (7/91) and a multispecies fish kill (6/94) on the Portsmouth shore area (Figure 1) hint at potential problems on the east side of Prudence Island also.

Conclusion

I hope that my presentation today convinces the environmental and research communities that we need to make a more concerted effort to better characterize the frequency and duration of hypoxic events during the critical summer months in Narragansett Bay. In addition, I hope that the evidence of low DO problems to at least the northern end of Prudence Island as well as Greenwich Bay convinces both the state regulators and the WWTF operators that it would likely benefit these areas of the bay to begin voluntary cost-effective operational changes where feasible to maximize nitrogen removal at the wastewater plants near the bay rather than wait another decade for the definitive model to be developed.

Table 1. Characteristic Impacts to Estuaries From Excess Nutrients

- Increased primary (plant) productivity
- Increased turbidity (lower water clarity)

Immediate Results:

- Loss of desirable habitat - submerged aquatic vegetation/seagrasses

- Shift in species phytoplankton composition
  (often from diatoms to dinoflagellates)

- Increased incidence/biomass of less desirable or undesirable plant species:

  - "nuisance" nontoxic species including seaweeds like *Ulva* sp. (sea lettuce)
  - toxic red tide (dinoflagellate) blooms

- Increased incidence of hypoxia ($\leq$2 ppm DO) & anoxia (0.0 ppm DO)

- Mass mortality, usually of benthic invertebrates
  (crab, shrimp, lobster, starfish, sometimes fish)

Long Term Results:

- Reduced diversity of bottom community
  (fewer species & dominated by opportunists)

- Shift from larger, long-lived benthic community to fewer species of smaller, shorter-lived opportunistic community

- Number of demersal fish species declined = fewer tot. # species + shift from demersal (bottom) fish (flatfish species) to water column (pelagic) species

- Population structure—shifts towards older individuals (more resistant to low DO) as young-of-year for bottom species die off

- Possible compromised immune systems (can cause increased incidence disease in fish, crabs, other invertebrates)

Table 2. How Low DO Conditions Affect Marine Life*

DO Levels	Consequences
5.0 mg/L or greater	• Few adverse effects expected
4.0 mg/L	• May reduce survival (30 percent) of very sensitive planktonic larvae of some crabs
3.0 mg/L	• Greater lethality (~75 percent) among the most sensitive planktonic crab larvae • Growth reduced (25 percent) in other, less sensitive planktonic crab larvae • Growth reduced in juvenile American lobsters by 25 percent • Bottom-living fishes begin to show low DO avoidance
2.5 mg/L	• Lethality threshold (15 percent) for the less sensitive planktonic larvae of crustaceans • Growth reduced (25 percent) in juvenile grass shrimp and summer flounder; 50 percent in American lobster • Most species of bottom-living fishes show low DO avoidance
2.0 mg/L	• Reduce growth (~ 50 percent) in juvenile summer flounder and juvenile grass shrimp • Lowest safe DO for survival of juveniles of several fish and crustaceans
1.5 mg/L	• Lethality in some juvenile fishes: pipe fish, 50 percent; winter flounder, 35 percent; summer flounder, 25 percent; Atlantic menhaden, 20 percent • Lethal threshold for some juvenile crustaceans: American lobster, sand shrimp, grass shrimp • At least 50 percent reduction in abundance of bottom-living fishes
1.0 mg/L	• High lethality (75-90 percent) in above mentioned fishes • Lethality (~ 25 percent) in three additional fishes: windowpane flounder, tautog, fourspine stickleback • Increased lethality (50 percent) in above mentioned juvenile crustaceans • Total avoidance by bottom-living fishes

*The Long Island Sound Study is using these data to identify dissolved oxygen levels protective of Long Island Sound aquatic resources and to guide management efforts. For additional information, please contact Mark Tedesco in the Long Island Sound Office at (203) 977-1541.

Table 3. Physical Conditions for Hypoxia in Narragansett Bay

CONDITIONS

- **Warm water** temp. (late June, July, August, Sept.)
- **Stratified water column** (warm temperature and salinity surface waters)
  Following significant rainfall event results in increased nonpoint source nutrient load and lower surface salinity
- **Calm winds & sunny days** following rainfall event
- **Low tidal currents** (neap tides - quarter moon)

RESULTS

- Biological productivity – (increase in both phytoplankton and macroalgal beds)
- Respiration exceeds photosynthesis causing DO depletion, especially in the bottom waters
- Daytime DO may be at supersaturation near surface during or just before events

UPWELLING EVENTS*:* Calm winds/anoxic bottom waters followed by sudden shift in winds results in upwelling of low DO bottom water into shallows. (All marine life attempting to leave the water: crabs climb pilings, large fish lay/swim in shallows and gasp at surface, etc.)

Table 4. Sensitivity of Typical Bay Organisms to Severe Hypoxia

Flounder and Other Bottom Fish and Squid—Adults can and do leave unless trapped. Problem: Many young-of-year may die if upwelling incidents in shallow waters of Upper Bay

Water Column (Pelagic) Fish Species (anchovies, herring, etc.)—Usually immune to bottom DO problems unless upwelling event or shallow water hypoxic event occurs. (Menhaden may quickly deplete DO when trapped in coves, etc. by predators like bluefish—especially if water is already low in DO—due to strong schooling behavior and large size/oxygen need. Therefore they are often implicated in fish kills.)

Bottom Invertebrates
Crustaceans—The typical victims: The most sensitive die first (crabs, shrimp, lobster, etc.), followed by starfish, sea urchins, sensitive marine worms, and shellfish.

Quahogs (hard shelled clams)—Very resistant, unless long anoxic event occurs.

Oysters—Usually resistant because they live in shallow waters, but there may be a die-off if upwelling occurs.

Softshell Clams—Fairly resistant if > 1 ppm DO, but will come out of sediments as DO goes below 1.0, with eventual mass mortality if DO event continues downward.

Marine Snails (whelks, etc.)—Sensitivity unknown (population seems to have decreased some places in the Upper Bay—cause unknown).

Table 5. Four Stages of Ecosystem Response to Low DO
(adapted from Diaz *et al*. 1995)

I. Aperiodic Hypoxia—DO usually good, then one year there is a sudden significant decrease to hypoxic DO levels ($\leq$2 ppm), followed by a return to 3 to 5 years of good DO conditions, then possible return hypoxic event.

Results—For bottom marine organisms sensitive to low DO, sudden high mass mortality—especially in deep waters. Includes temporary elimination of some benthic commercial fisheries during and after low DO event.

***1st SIGN:** Bottom fish disappear, but trawls may get sudden increase in invertebrates, followed by several days with dead benthic organisms or no organisms where normally plentiful.

II. Moderate Periodic (Seasonal) Hypoxia—DO decreases each summer but does not go far below 2 ppm.

Results—Sensitive species die off. Bottom fish avoid the area while low DO occurs. Only tolerant bottom marine species remain during the event. Significant benthic mortality and lowered diversity, depending on how low DO goes and how long it goes on and risk of upwelling impact to shallow waters.

NOTE : Can have anoxic “pulse” (severely low hypoxic event of <0.2 ppm DO at sediment/water interface) resulting in wide spread die-off.

III. Severe Periodic (Seasonal) Hypoxia/Anoxia—Becomes a low-diversity “pulsed system”—most benthic organisms are pioneer opportunists, living 1-year lifetime, usually without reproduction.

Results—Energy in benthic community flows in 1-year “pulses” towards a bacteria-only ending (anoxia), with opportunists dropping out of the plankton and replacing last year’s crop each time. Benthic mortality is not always obvious since sensitive bottom species never get established. Bottom community is made up of low-diversity pioneer opportunist species. Bottom fish populations often decrease and are replaced by water column species like herring and anchovies.

IV. Severe Persistent Hypoxia & Anoxia—(e.g., Deep fiords) DO never rises above 2 ppm, and usually remains close to 0 ppm at the sediment/water interface.

Results—Only special sulfide-loving bacteria exist

Table 6. Sources of Data on Low DO and Related Information

SOURCE	MEASUREMENT/ IMPACT
The State of the State's Waters – Rhode Island, CWA Section 305(b) Report. 1988, 1990, 1992, 1994, 1997.	Reported fish kills/sporadic discrete DO data
Frithsen, J. 1990. The Benthic Communities Within Narragansett Bay. NBP Report *#NBP-90-28.*	Benthic Community Assessment
Granger, S., B. Buckley, M. Traber, M. Brush, M. Richardson, and S. Nixon. 1998.	Discrete DO data, Greenwich Bay
Spaulding, M.L., S. Sankaranarayanan, L. Erikson, T. Fake, and T. Opishinski. 1998.	Continuous DO readings, Greenwich Bay
Data Report to New England Power Company Brayton Point Station Dissolved Oxygen Assessment Field Studies. ASA Project 96-076.	Continuous DO readings, Mount Hope Bay
King, John. 1998. Personal Communication.	Anoxic Surface Sediments
Strobel, Charles. 1998. Personal Communication.	Benthic trawl catch and hypoxic bottom DO, West Passage east of Allens Harbor, week of June 22,1998
Turner, C. 1997. Development of a Total Maximum Daily Loading for nutrients: Results in the Providence and Seekonk Rivers.	Discrete DO
Valente, R., D. Rhoads, J. Germano, and V. Cabelli. 1992.	Benthic REMOTS analyses

Figure 1. RIDEM 1986 to 1998 Hypoxia/Mass Mortality Investigations and Other Low DO Evidence

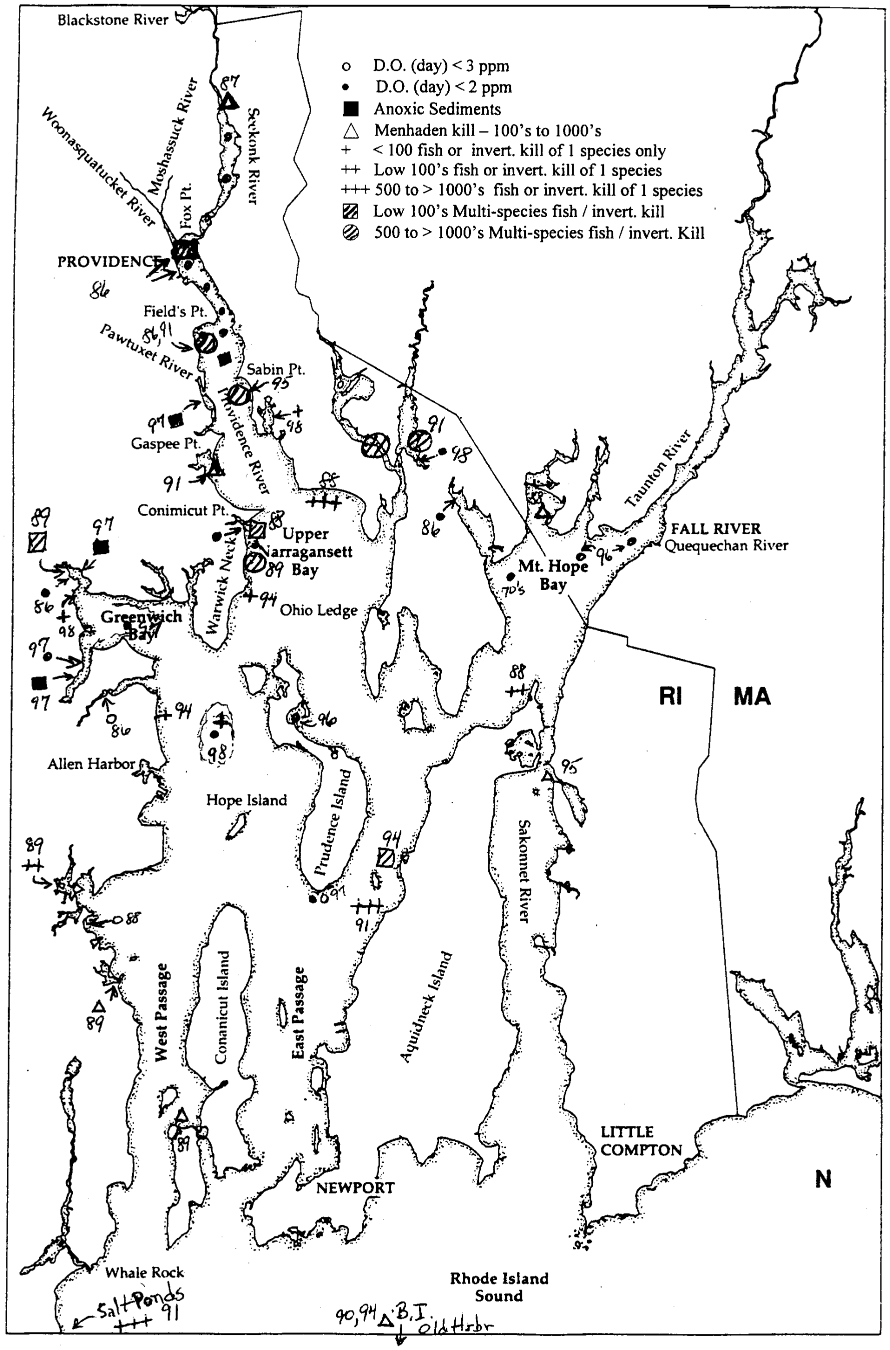
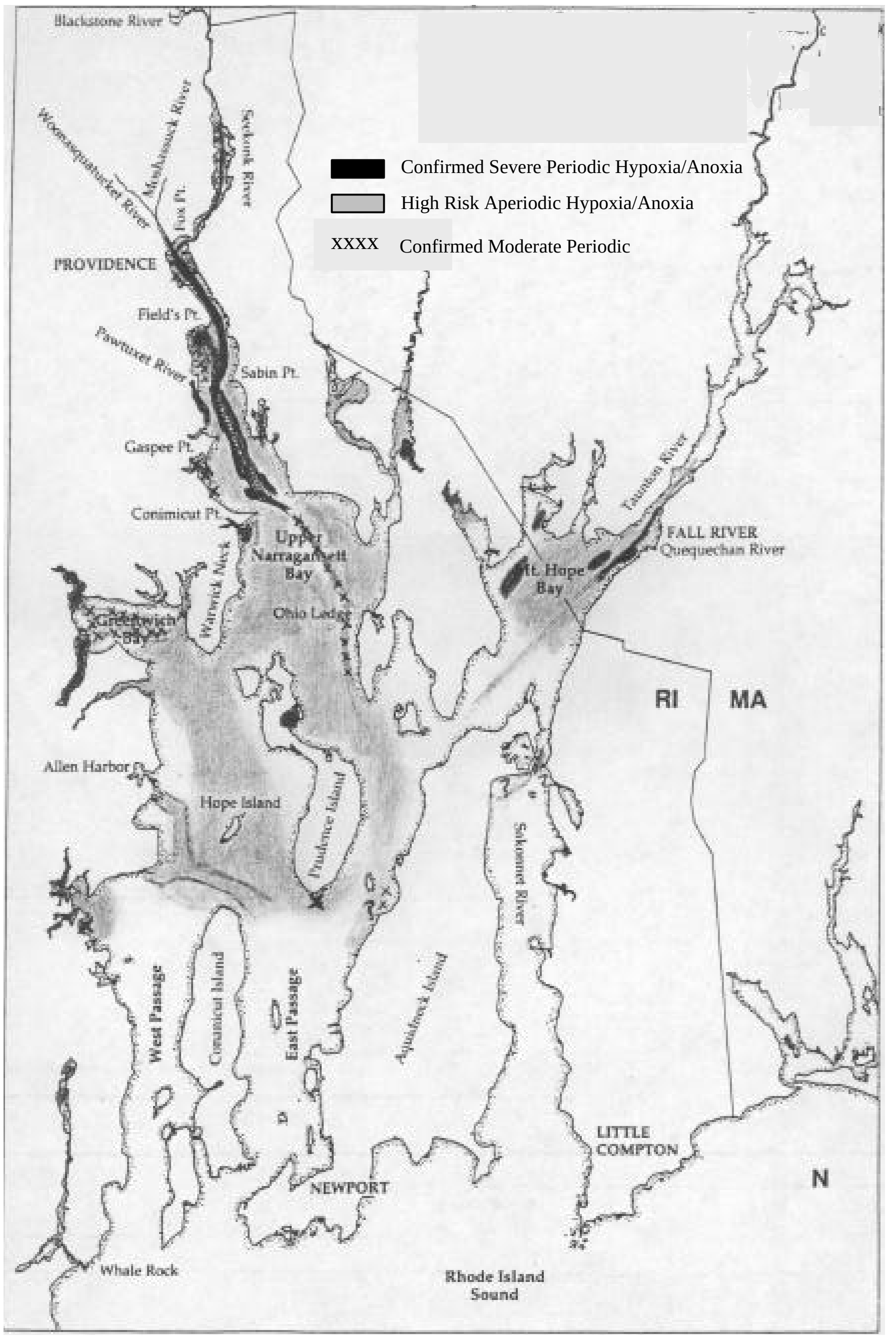


Figure 2. Hypoxia Risk Map of Narragansett Bay 1998



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Status of Rhode Island Treatment Plant Upgrades

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Introduction

The purpose of this presentation is to discuss:

- Which Rhode Island facilities currently have discharge limits for nutrients
- Why the limits were assigned
- The future of nutrient limits for point sources in the state—what we have planned for the near future.

The RI DEM is delegated authority by the EPA to implement the National Pollutant Discharge Elimination System (NPDES, called RIPDES in Rhode Island) program in the state. Our charge is to issue discharge permits to point source discharges that will protect the state's water quality. These permits are developed using two methods:

1. Technology-based limits based on effluent guidelines or best professional judgement.
   The EPA has analyzed industries and sewage treatment facilities throughout the country and developed effluent limitations that should be met by a variety of dischargers. An example of technology-based limitations is the requirement for secondary treatment (30 mg/L BOD5 and 30 mg/L TSS) for municipally owned sewage treatment plants. When effluent guidelines have not been developed for a certain discharger, limits are developed using best professional judgement. To develop these limits we carefully examine the industry and its proposed treatment system and compare it to similar facilities in the region. We examine the industrial processes and the wastewater characteristics and develop effluent limitations that are both economically feasible and environmentally protective.

2. Water quality-based limits developed on a case-by-case basis using water quality models.
   In some cases, the discharge of waste with pollutants at technology-based limits will not protect the water quality standards assigned to the receiving waters. In these cases, we must calculate more restrictive limits that will maintain the quality of the receiving waters. Developing these permits requires data on the characteristics of the wastewater and the receiving waters, and mathematical models that predict the fate and transport of the pollutants once they are discharged.

Since 1993, we have been issuing water quality-based permit limits for nitrogen as ammonia (NH_3) based on EPA's water quality criteria calculated to prevent toxicity to aquatic organisms. For discharges to Narragansett Bay, we use various effluent mixing models (some that EPA developed) to evaluate dilution close to the sewage outfall.

Status of Rhode Island Treatment Plants

Table 1 shows the status of ammonia limitations for Rhode Island's 19 municipal WWTFs. Six facilities (Cranston, Narragansett Bay Commission Bucklin Point (draft), Warwick, West Warwick, Westerly and Woonsocket) have toxicity-based discharge limits for ammonia in the 2 to 5 mg/L range. Seven facilities (Bristol, East Greenwich, Jamestown, Newport, Scarborough, South Kingstown and Warren) discharge well below the ammonia concentration needed to prevent ammonia toxicity and are not given permit limitations. The six remaining facilities (Burrillville, East Providence, Narragansett Bay Commission Fields Point, New Shorham, Rhode Island Economic Development Corporation and Smithfield) have not yet been evaluated.

In some situations, the oxygen consumed by ammonia decay can significantly affect in-stream oxygen levels. For example, on the Blackstone River, a DO model has been calibrated that takes into account oxygen depletion resulting from ammonia decay. We are also developing a model for the Providence/Seekonk River that will consider DO and nutrient dynamics.

When we review or issue permits for facilities required to limit ammonia, we now give them a warning that they will soon be asked to begin denitrification. We are asking design engineers to look seriously at engineering options for denitrification as well as nitrification.

All of those involved – state regulators, engineers, permittees – are working together to answer the following questions:

1. What is a reasonable reduction in total nitrogen load to Rhode Island's waters that we can achieve in the short term?
2. Will these reductions provide adequate long term protection?

Table 1. Status of Ammonia Limitations and Facilities Planning Efforts in Rhode Island

	Permitee	Existing Facilities Design Flow (MGD)	Flow Monthly Ave (MGD)	Percent of Flow Capacity	Monthly Average Ammonia Limit (mg/l)	Facility Planning (FP) Status
1.	Bristol WWTF	3.79	3.05	80.5	N/A	Currently preparing FP update
2.	Burrillville Sewer Comm.	1.50	0.81	54.0	Not Evaluated	
3.	Cranston WWTF	23.00	11.81	51.4	2	FP update under DEM review includes evaluation of N and P removal.
4.	East Greenwich WWTF	1.24	0.86	69.4	N/A	
5.	East Providence WWTF	10.40	6.21	59.7	Not Evaluated	
6.	Jamestown WWTF	0.73	0.43	58.9	N/A	
7.	Narragansett Bay Commission – Bucklin Pt.	31.00	22.49	72.6	4.1 (Draft)	FP update approved. Currently preparing preliminary design includes N removal.
8.	Narragansett Bay Commission – Fields Pt.	65.00	44.19	68.0	Not Evaluated	
9.	New Shoreham WWTF	0.30	0.07	23.3	Not Evaluated	
10.	Newport WWTF	10.70	8.69	81.2	N/A	
11.	RI Economic Development Corp.	1.78	0.9	50.6	Not Evaluated	
12.	Scarborough WWTF (Town of Narragansett)	1.41	0.64	45.4	N/A	
13.	Smithfield Sewer Authority	3.50	1.56	44.6	Not Evaluated	
14.	South Kingstown WWTF	5.00	2.57	51.4	N/A	
15.	Warren WWTF	2.01	1.91	95.0	N/A	
16.	Warwick WWTF	5.00	3.46	69.2	2	FP update approved. Preliminary design under DEM review includes N and P removal.
17.	West Warwick WWTF	7.89	5.09	64.5	2	Approved. Preliminary design under DEM review includes N and P removal.
18.	Westerly WWTF	3.30	2.32	70.3	5.5	FP update drafted, RIDEM-issued comments will include evaluation of N removal.
19.	Woonsocket WWTF	16.00	8.27	51.7	5.8 (Draft DO based limit = 2)	Not required to commence until DO-based limits are finalized.

***NOTE:

N/A Comparison of effluent data to allowable discharge levels demonstrated a limitation was not necessary (e.g. the discharge did not have a reasonable potential to cause or contribute to a violation of the aquatic life criteria).

Not Evaluated: Allowable discharge limitations have not been determined.

Scarborough WWTF—Approved Facilities Plan projects ADF of 1.96 MGD.

South Kingstown—Approved Facilities Plan projects ADF of 6.866 MGD.

Warwick—FP update approved in 1997. Approved ADF of 7.7 MGD.

Westerly—Draft FP update reviewed by RIDEM, includes aggressive I/I reduction program and change in ADF from 3.3 to 2.89 MGD.

West Warwick—FP update approved in 1997, ADF of 9.5 MGD, Preliminary Design Report (PDR), revised the ADF to 10.21 MGD.

Table 2. Major Municipal WWTFs Average of Discharge Data Collected January 1995 to December 1997

Permit Name	Flow Monthly Ave (MGD)	Ammonia Daily Max (mg/l)	Nitrate Daily Max (mg/l)	Nitrite Daily Max (mg/l)	NH3+NO2+NO3 (LBS/DAY)	Percent of Total N Loading	NUMBER OF DATA PTS.
BRISTOL WWTF	3.05	22.26	3.74	0.23	667.21	4.1	8
BURRILLVILLE	0.81	15.65	1.97	0.83	124.64	0.8	36
CRANSTON	11.81	17.37	0.89	0.15	1813.3	11.1	36
EAST GREENWICH	0.86	9.15	3.73	0.79	98.05	0.6	36
EAST PROVIDENCE	6.21	2.1	8.33	0.55	568.67	3.5	36
JAMESTOWN	0.43					0.0	
NARRAGANSETT BAY COMMISSION—BUCKLIN	22.49	11.19	3.6	0.79	2922.29	17.8	35
NARRAGANSETT BAY COMMISSION—FIELDS	44.19	9.24	5.45	0.27	5513.43	33.6	35
NEW SHOREHAM	0.07	5.65	13.21	0.25	11.16	0.1	36
NEWPORT	8.69	9.04	1.45	0.22	776.2	4.7	35
RIEDC/QUONSET	0.9	1.55	7.01	0.82	70.41	0.4	36
SCARBOROUGH WWTF (Town of Narragansett)	0.64					0.0	
SMITHFIELD	1.56	12.35	1.67	0.68	191.25	1.2	36
SOUTH KINGSTOWN	2.57	4.81	3.65	0.26	186.9	1.1	12
WARREN	1.91	9.39	1.67	0.44	183.19	1.1	23
WARWICK	3.46	28.86	3.03	1.77	971.31	5.9	36
WEST WARWICK	5.09	11.91	1.84	0.24	593.88	3.6	36
WESTERLY	2.32	10.42	0.26	0.18	210.13	1.3	36
WOONSOCKET	8.27	19.3	2.26	0.29	1507.03	9.2	36
TOTAL					**16409.05**		

Note: Highlighted data is suspect and currently under review
Scarborough WWTF - Approved FP projects ADF of 1.96 MGD
South Kingstown – Approved FP projects ADF of 6.866 MGD
Warwick - FP update approved in 1997. Approved ADF of 7.7 MGD.
Westerly - Draft FP update reviewed by RIDEM, includes aggressive I/I reduction program and change in ADF from 3.3 to 2.89 MGD
West Warwick - FP update approved in 1997, ADF of 9.5 MGD, Preliminary Design Report (PDR), revised the ADF of 10.21 MGD.
Increasing all facilities to their current design flows increases the N load by 55 percent to 25,490 lbs/day.

Environmental Protection Agency's National Strategy for the Development of Regional Nutrient Criteria

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Introduction

Nutrients pose water quality problems throughout the United States. The National Water Quality Inventory: 1996 Report to Congress cites nitrogen and phosphorus as one of the leading causes of water quality impairment in our nation's rivers, lakes, and estuaries. Nutrients have been implicated with hypoxic zones in the Gulf of Mexico and Long Island Sound and have affected oxygen levels in Narragansett Bay.

The national response to the nutrient problem has been limited primarily because of concerns over the scale of the problem and because of the tremendous variability of nutrient conditions, both natural and cultural, throughout the nation. The only national water quality criteria for nutrients are for nitrate and phosphorous, both developed to prevent toxic impacts and not to protect against eutrophication. Individual states have developed and adopted their own statewide criteria or have developed case-specific criteria based on their best professional judgement.

Regional Nutrient Criteria

In 1998, EPA launched a national strategy to develop regional nutrient criteria in response to water quality problems in marine and fresh waters. The President's Clean Water Action Plan, a national agenda for addressing environmental problems, was presented in the Federal Register in March. The development of nutrient criteria is one of the key aspects of this plan.

Key elements of the national nutrient strategy are:

- Use of a regional approach that examines differences in waterbody types in developing nutrient water quality criteria
- Development of technical guidance documents for each waterbody type (streams and rivers, lakes and reservoirs, estuaries and coastal waters, and wetlands) that will establish methods for assessing trophic status and develop region-specific nutrient criteria
- Establishment of an EPA national nutrient team with regional nutrient coordinators to develop regional databases and to promote local involvement
- Development by EPA of nutrient water quality criteria guidance in the form of numerical regional target ranges for states and tribes to use in implementing state management programs to reduce overenrichment in surface waters
- Monitoring and evaluation of the effectiveness of nutrient management programs as they are implemented

Ambitious deadlines have been established. The technical guidance for lakes and reservoirs was due for completion in December 1998; the rivers and streams guidance is due in March 1999; and the marine and estuarine guidance is due for completion in 2000. Wetlands guidance is expected in 2001. States and tribes are expected to have adopted nutrient criteria within three years of the completion of these documents, or by December 2003.

The detail of the guidance documents will reflect the technical appendices that are put together by the regional development teams. Since every region will have its own team, each is free to take very different approaches to criteria development. We expect that there will be numeric nutrient criteria adopted by states and used to develop discharge permit limits within five years.

The Chesapeake Bay Program and Point Source Nutrient Reductions

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The Chesapeake Bay Program: An Overview

The Chesapeake Bay Program is the unique regional partnership that has been directing and conducting the restoration of the Chesapeake Bay since the signing of the historic 1983 Chesapeake Bay Agreement. The Chesapeake Bay Program partners include the states of Maryland, Pennsylvania, and Virginia; the District of Columbia; the Chesapeake Bay Commission, a tri-state legislative body; and the Environmental Protection Agency, representing the federal government.

As the largest estuary in the United States and one of the most productive in the world, the Chesapeake was this nation's first estuary targeted for restoration and protection. In the late 1970s, scientific and estuarine research on the bay pinpointed three areas requiring immediate attention: nutrient overenrichment, dwindling underwater bay grasses and toxic pollution. Once the initial research was completed, the bay program evolved as the means to restore this exceptionally valuable resource.

Since its inception in 1983, the bay program's highest priority has been the restoration of the bay's living resources—its finfish, shellfish, bay grasses, and other aquatic life and wildlife. Improvements include fisheries and habitat restoration, recovery of bay grasses, nutrient and toxic reductions, and significant advances in estuarine science.

Examples of specific actions initiated by the bay program include a watershed-wide phosphate detergent ban, the introduction of agricultural best management practices, BNR at wastewater plants, and a public education campaign emphasizing the role each of the watershed's 15 million residents plays in the restoration.

Nutrient Reduction Strategies

In the 1987 Chesapeake Bay Agreement, the executive council set a goal to reduce the nutrients nitrogen and phosphorus entering the bay to 40 percent below 1985 levels by the year 2000. Achieving a 40 percent nutrient reduction will ultimately improve the oxygen levels in bay waters, allowing aquatic life to flourish.

In the 1992 amendments, the bay program partners confirmed the goal and agreed to maintain the 40 percent goal beyond the year 2000. As a result, Pennsylvania, Maryland, Virginia, and the District of Columbia began developing tributary strategies to achieve the nutrient reduction targets.

Nutrient loadings to the bay and rivers are being reduced through upgrades at sewage treatment plants, including the implementation of BNR at some facilities. A relatively new technology, BNR has proved to be extremely effective in reducing nutrients. However, BNR has only been implemented at 33 of the 315 major municipal wastewater treatment plants in the bay region. About 90 facilities are expected to be on-line by the year 2000 or shortly thereafter. Among the federal WWTFs in the bay region, only one of the seven major facilities has implemented BNR. By 2000, four additional facilities are expected to have implemented BNR, with another expected to come on-line shortly after 2000.

Phosphorus Progress to Date

Between 1985 and 1996, phosphorus point source loads to the bay from participating states have been reduced by 51 percent. This 5 million pound reduction was due to the implementation of phosphate detergent bans that went into effect in each of the states between 1985 and 1990 and the implementation of effluent standards for phosphorus and concurrent wastewater treatment upgrades in each of the jurisdictions.

By the year 2000, point source phosphorus loads are estimated to be 58 percent lower than 1985 loads delivered to the bay. The additional reductions beyond those observed through 1996 are due primarily to industrial facilities sending their wastewater for treatment at municipal facilities operating BNR. While phosphorus discharge concentrations from municipal facilities should remain steady in response to specific regulatory discharge limits, increases in flow due to population growth will cause an increase in phosphorus loads from municipal facilities shortly beyond 2000, unless more action is taken to reduce total phosphorus.

Nitrogen Progress to Date

Between 1985 and 1996, nitrogen loads from point sources in the participating states have been reduced by 15 percent, or 12.6 million pounds. Since 1985, 33 of 315 major municipal WWTFs in the watershed have upgraded to BNR technologies. This advanced technology reduced effluent concentrations from 18 milligrams per liter to eight milligrams per liter and kept the municipal loads in check, in spite of an 11 percent population increase over the last decade. The diversion of industrial effluent to plants with BNR—where it can be treated more effectively—combined with reductions achieved through industrial wastewater treatment upgrades, in-process manufacturing changes and facilities going off-line has played a key role in achieving this level of reduction. In the future, as more municipal plants upgrade, the proportion of reductions from these plants may increase.

By the year 2000, a total of 71 major municipal WWTFs will be operating BNR, resulting in an estimated 10 million pounds, or a 28 percent reduction in municipal point source nitrogen loads delivered to the bay since 1985. Upon full implementation of the tributary strategies, an additional 19 municipal facilities will be operating BNR resulting in a further 5 million pound reduction since 1985. Implementation of BNR at six of the seven major federal facilities will further decrease loadings by 220,000 pounds. After full tributary strategy implementation, point source nitrogen loads from municipal, industrial and federal facilities will be reduced by 29 million pounds—a 34 percent decrease since 1985.

Closing the Gap by the Year 2000

The 1997 meeting of the bay program's executive council called on the bay program in Directive 97-1 to take measures to close the nutrient reduction gap.

- Accelerate nutrient reduction at wastewater plants currently scheduled for improvements after 2000.

For example, eight facilities identified for treatment upgrades in Maryland's tributary strategies will not have BNR in place by 2000. Almost half of this potential reduction could be achieved through a trading program the Maryland Department of the Environment is considering in partnership with local municipalities between the largest of these eight facilities, Patapsco and Maryland's Back River facility. Rather than operating BNR at Patapsco, which is experiencing technical problems in their BNR pilot studies, additional reductions on the order of 700,000 pounds per year nitrogen delivered to the bay could occur through methanol addition at Back River, which will already be operating a BNR process by 2000.

- Implement low-cost modifications where accelerated installation is not feasible, in order to obtain short-term partial nutrient reductions.

For example, 10 facilities in Virginia's Potomac Basin tributary strategy will not have BNR in place by 2000. Implementing BNR at these 10 facilities would result in the removal of 4 million pounds of nitrogen delivered every year to the bay. While acceleration of BNR installation may not be feasible at these facilities, certain low-cost modifications may be possible while the upgrades are being implemented, thereby achieving some nutrient reductions. Further investigation is warranted into recent recommendations that suggest that two of these facilities could employ low-cost modifications to achieve removals of approximately 500,000 pounds per year of nitrogen delivered to the bay.

- Encourage voluntary efforts to achieve additional interim reductions from major wastewater treatment plants where nutrient reduction technologies are in place or will be by 2000, but where still higher levels of removal can be obtained from process changes or year-round operation, and support those efforts through innovative federal, state, and local cost-sharing arrangements.

For example, the Blue Plains Sewage Treatment Plant, a regional facility located in the District of Columbia and the largest sewage treatment plant in the bay region, is exploring the applicability of a three-stage BNR process under a pilot project involving half the flow entering the facility. Following an evaluation of the results of the pilot project, if it is concluded that the process modifications being studied are feasible, full-scale plant modifications will be implemented. The process being tested shows potential for reducing the effluent concentrations of nitrogen below the planned 7.5 milligrams per liter. Other technologies for further reduction of nitrogen also will be tested. However, innovative federal, state and local cost-sharing methods will have to be identified, and issues of permit limit and equity will have to be resolved before the final BNR plan for Blue Plains is developed and implemented.

- Ecourage commitments for additional nutrient reductions from private sector facilities with high loading rates.

For example, many industrial facilities have already made significant nutrient reductions, largely on a voluntary basis, through in-process changes, end-of-pipe treatment upgrades, or hook-ups to municipalities with BNR. Implementation of nitrogen removal technologies at 15 of the highest nutrient-discharging facilities with no known nutrient removal practices shows the potential for further reducing nitrogen loads to the bay by at least 1.7 million pounds per year. The Chesapeake Bay Program partners plan to work with these facilities, either through a pollution prevention program, such as Businesses for the Bay, or other means to seek additional nutrient reductions.

- Initiate cooperative efforts with non-signatory states.

It is estimated that the other bay basin states—New York, West Virginia, and Delaware—contribute over 12 percent of the total nitrogen and 9 percent of the total phosphorus loadings delivered to the bay. Targeted nutrient reduction actions taken in cooperation with these jurisdictions can result in further reduced nutrient loadings to the bay.

<u>Advantages of Using Point Source Gap Closers</u>

The Chesapeake Bay Program has targeted point sources for a number of reasons:

- Point source reductions can be realized quickly. Nonpoint source controls take place after a 10 to 20 year time lag, point source reductions can be realized as soon as controls are installed.
- Point source reductions are consistent and ongoing and work regardless of storm events.
- Reductions in point source loads can be accurately predicted and tracked.
- There is the greatest room for reductions based on available technologies.
- Population growth is producing the fastest growth in point source loads.

Specific Benefits of Biological Nutrient Removal

Point source reductions using BNR have been proven cost effective as shown in Table 1. In fact, savings can be realized through[1]:

- Reduction in energy costs (due to reduction in aeration energy requirements)
  20 to 30 percent savings
- Reduction in chemical usage (denitrification naturally adjusts the pH)
  50 percent or more savings
- Reduction in the amount of waste sludge produced
  5 to 15 percent savings

BNR was thought to cost on the order of $35/lb total Nitrogen removed only five years ago. Since this time, technological advancement has occurred such that BNR is highly cost-competitive with other nutrient removal techniques.

What Next?

The Chesapeake Bay Program will continue to promote cost-effective nitrogen reduction at all point sources on a voluntary basis. However, EPA regulatory initiatives are on the horizon, including the development of total maximum daily loads (TMDL) and the development of nutrient criteria.

EPA Region III policy on TMDLs says that waters violating DO standards due to nutrient overenrichment should be listed on the state's CWA Section 303(d) list. Therefore, the Chesapeake Bay and its tributaries should be listed and scheduled for regulatory action to address the excess load. EPA is also scheduled to establish regional nutrient criteria for estuaries by 2000, followed by state adoption of nutrient criteria. These standards will provide further regulatory support for nutrient reductions at all point sources.

[1] Generally applicable where facilities are already required to remove ammonia.

Table 1. Nitrogen Removal Cost Analysis Summary

Management Practice	Cost per pound N reduced	Cost per person per day[5]
Urban best management practices[1]	$142.64	
Conservation tillage[1]	$7.44	
Animal waste[1]	$7.17	
Nutrient management[1]	$0.61	
BNR (to 7 – 8 mg/l):		
• Average of 22 Maryland facilities with BNR recently implemented[2]	$3.64 (Actual cost)	2 cents a day
• Engineering study of 5 metropolitan Virginia facilities[3]	$5.38 (est. cost)	3 cents a day
• Twelve facilities evaluated to date in CBPO BNR study[4]	$0.02 – 4.95 (est. cost)	Less than 0.5 cent to 3 cents a day

1 Shuyler, L.R. et.al. (1995). *Water Science Technology*. 31(8).
2 From MDE MNR Capital Cost 7/96 – list amortized over 20 years including 7 percent O&M.
3 Engineering Science (consultant document) 1993 – for Alexandria, Arlington, Blue Plains, Lower Potomac, Mooney, Piscataway.
4 CBPO Preliminary BNR evaluations by Randall, et. al.
5 Assumes 10 million people on sewer in watershed (1990 U.S. Census), and a reduction of 20.4 million pounds achieved if all significant watershed facilities implemented BNR (to 7 to 8 mg/l) by 2000. Assume half of this cost for facilities receiving 50 percent match grants.

Sarasota Bay Florida: A Nutrient Control Success Story

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Introduction

During the past 50 years, human activities have caused a slow but steady decline in the general health of Sarasota Bay. Damage to the bay began with massive dredge-and-fill projects from 1950 to 1960 and has continued with the rapid growth in the bay's watershed.

Nitrogen is a principal pollutant affecting bay water quality. Excess nitrogen stimulates algal growth, which reduces light penetration to submerged seagrasses and depletes oxygen from the water. Nitrogen loading into Sarasota Bay has tripled since intensive development began. If no actions are taken, nitrogen loadings are projected to increase another 8 percent during the next 20 years, and 16 percent when the area is fully developed according to existing plans.

Nitrogen comes from wastewater (including small and large wastewater treatment plants), groundwater (from septic systems and small treatment plants) and stormwater (including fertilizers from lawn care and agriculture). Nitrogen is also introduced in rainfall from acid rain.

Nutrient Controls

Nitrogen from point sources has decreased 28 to 38 percent since 1988, in large part due to the Grizzle-Figg legislation that requires direct discharge of wastewater to meet advanced wastewater treatment (AWT) standards – 3 mg/L for nitrogen. The Grizzle-Figg legislation has also indirectly promoted large scale recovery of wastewater. Reclaimed water has become a valuable commodity in the Sarasota Bay area. The entire Sarasota Bay watershed now reclaims 46 percent of its wastewater for irrigation, both decreasing the amount of wastewater discharged to the bay and offsetting potable water demands. Manatee County installed a deep well injection system at its southwest regional plant in northeast Sarasota Bay that virtually eliminated discharge of wastewater to the bay in that area. The county is now aggressively pursuing aquifer storage and recovery to reclaim this water. Northern Sarasota Bay now receives little or no wastewater discharge annually. The city of Sarasota upgraded its treatment technology to AWT in 1991 while providing a concurrent increase in the amount of effluent available for reuse, which has resulted in a 95 percent nitrogen load reduction from the plant and a 14 percent decline in baywide loadings. Sarasota County is currently pursuing the replacement of 10,000 septic tanks in the Phillippi Creek basin with a central sewer system. In 1998, a one cent sales tax in Sarasota County passed by an overwhelming margin and allocated 39 million dollars for sewer expansion beginning in the year 2000.

In the Sarasota Bay watershed, the largest single land use is residential. The intensive use of fertilizers on lawns is thought to be a significant source of nitrogen entering the bay. To reduce nitrogen loads carried by stormwater runoff, the Florida Yards and Neighborhoods Programs was launched in 1993. The program advocated practical ways to reduce stormwater pollution through improvements to residential landscape design and maintenance. In addition, stormwater management master plans have been developed for major tributaries in Sarasota Bay. It is estimated that nitrogen loading has been reduced by more than 2 percent baywide due to stormwater improvement projects.

Historically, the bay had lost about 30 percent of its seagrass beds since the 1950s. Excessive nitrogen in the bay from wastewater and stormwater has harmed seagrass beds. An overabundance of nitrogen and other nutrients stimulated algal growth, which blocks the penetration of sunlight in the water, thus causing a reduction in the growth of seagrasses. Due largely to the nutrient load reductions outlined above, seagrasses have increased 20 percent baywide. Approximately 44 percent of historic losses have been recovered since 1988. The new seagrasses that have returned are expected to provide habitat for 100 million more fish, 68 million more crabs, and 310 million more shrimp than existed in 1988.

Denitrification Technologies and Costs of Upgrading WWTFs: Connecticut's Approach

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Introduction

Long Island Sound is the embayment between New York's Long Island north shore and Connecticut's south shore. It is boarded on the west by the East River, a tidal strait and on the east by Block Island Sound. In 1985 the EPA National Estuary Program selected Long Island Sound as an estuary of national significance, and the Long Island Sound Study (LISS) was initiated. The LISS is a partnership between the states of Connecticut and New York, EPA regions 1 and 2, and New York City. The LISS is charged with identifying the most pressing environmental problems affecting the sound and producing a Comprehensive Conservation and Management Plan (CCMP) to address these problems. The program has had very good cooperation and support from citizens in New York and Connecticut, their respective legislators and treatment plant operators.

The LISS has identified low DO, or hypoxia, as a major issue of concern for the sound. The causes of hypoxia are complex, but early modeling identified point sources of nitrogen from municipal wastewater treatment plants as a major contributor to the offshore hypoxia. Point source discharges account for greater than 75 percent of the total human-caused loads entering Long Island Sound. Nitrogen fuels the growth of phytoplankton, which are consumed by bacteria when they die. Bacterial respiration of oxygen creates hypoxia.

The LISS has implemented a phased approach to address nitrogen loads.

Phase I: No Net Increase of Nitrogen to Long Island Sound

The CCMP recommended reducing nitrogen discharges from municipal wastewater treatment plants in Connecticut that discharge directly into western Long Island Sound. A baseline 1990 load of 17,460 lbs/day from these treatment plants was calculated and in 1991, a no-net increase policy was established to hold future total nitrogen loads to the 1990 level. Other Phase 1 commitments include:

- Encouraging nutrient removal at Connecticut sewage treatment facilities
- Instituting nitrogen removal planning at key sewage treatment plants
- Investigating the relevance of nitrogen point sources throughout the state to hypoxia in Long Island Sound

- Integrating nitrogen reduction activities into state nonpoint and stormwater management plans and their implementation
- Planning for nitrogen control in major river basins, with specific attention to nonpoint sources
- Estimating reductions in atmospheric nitrogen that might come about through implementation of the Clean Air Act
- Developing a monitoring plan for Long Island Sound to track implementation benefits

Phase II: Initial Nitrogen Reductions to Long Island Sound

In 1994, Connecticut, New York, and the EPA agreed to take steps to reduce nitrogen loads to Long Island Sound. These commitments included:

- Implement BNR at selected sewage treatment facilities in southwestern Connecticut. In 1993, the Department of Environmental Protection initiated a BNR Clean Water Fund grant program with a 15 million dollar budget to reduce nitrogen at key treatment plants. The program provided 100 percent funded grants to municipalities to implement BNR at 11 of the 16 treatment plants in the targeted area. As of the end of 1995, the municipalities that were awarded grants had attained the 25 percent nitrogen reduction goal established for the Phase II reductions.
- Investigate expanding stormwater permitting programs to regulate communities with populations of fewer than 100,000 that border Long Island Sound within high priority management zones.
- Study point and nonpoint nitrogen loading in the city of Stamford to begin to assess the feasibility of a point/nonpoint trading program.
- Provide technical assistance to coastal municipalities to address impacts of hypoxia in their municipal regulations and plans of development.
- Advocate for the use of the June nitrate test on agricultural lands to ensure that the application of fertilizer does not exceed the need.

Phase III: Major Nitrogen Load Reductions to Long Island Sound

The Long Island Sound CCMP committed Connecticut to a third phase of implementation to take effect once the modeling was completed and an agreement on the level of nitrogen reduction was reached. Phase III commitments are under development. It is likely that the existing load of human-generated nitrogen will need to be reduced by as much as 60 percent to make meaningful improvements in DO levels in the sound. Most of that reduction will come from sewage treatment plants, but nonpoint and atmospheric sources will have to be addressed if nitrogen reduction goals are to be met.

The following items show the steps that will be followed to develop Phase III reductions:

1. Establish DO levels that protect the living resources of Long Island Sound. Bottom waters on a daily average should be at least 3.5 mg/l and never fall below 2.0 mg/l to provide a reasonable level of protection.

2. Determine how much nitrogen can be effectively removed in Phase III to maximize progress toward the target DO levels.
3. Plan the distribution of the nitrogen reduction among the management zones established around the sound. Twelve management zones have been defined around the sound. Six are located in Connecticut. Each management zone will have the same percent reduction assigned to it.
4. Establish a flexible system for achieving the nitrogen reduction targets to ensure cost-efficiency.
5. Develop a schedule for achieving nitrogen reduction targets with periodic formal checkpoints. A 15 to 20 year implementation schedule will be set for Phase III activities within Connecticut. During the periodic reviews, CT DEP will evaluate whether final targets can be raised to incorporate technical advances in nitrogen removal.

Progress to Date

The CT DEP, in partnership with several municipalities, has made great strides in reducing the nitrogen load to Long Island Sound. Fifteen sewage treatment plants in southwestern Connecticut have achieved more than a 25 percent reduction in the aggregate nitrogen load through a low-cost retrofit program. $250 million in Clean Water Fund loans have been used to upgrade sewage treatment plants. Since 1990, Connecticut has managed to reduce the statewide point source nitrogen load by an estimated 20 percent through cooperative state-municipal-private efforts.

Nutrient Addition and Nutrient Removal in Biological Systems

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Introduction

The adverse impacts of discharging the nutrients nitrogen and phosphorus to the aquatic environment are being increasingly recognized (National Research Council, 1993). Ammonia-nitrogen discharges can lead to increased oxygen demand in the receiving stream and depressed DO concentrations. Ammonia-nitrogen can be toxic to aquatic organisms, depending on the pH and temperature conditions within the receiving water body. Nitrite-nitrogen can also be quite toxic. Nitrogen and phosphorus discharges can enrich receiving water bodies, resulting in the undesirable growth of algae and other aquatic plants known as eutrophication. Nitrate-nitrogen discharges can also be a public health concern if they exceed the 10 mg-N/L primary drinking water standard. Table 1 summarizes the impacts of nutrient discharges on receiving waters.

Table 1. Impact of Nutrient Discharges

Nutrient	Impact
Ammonia	Oxygen Demand, Toxicity
Nitrite	Toxicity
Nitrate	Water Supply Impacts
Total Nitrogen	Eutrophication
Total Phosphorus	Eutrophication

Biological Nutrient Removal

As a consequence of the impact of nutrient discharges, nutrient limitations are increasingly being added to the discharge permits of wastewater treatment plants. Chemical systems are used frequently to remove phosphorus. However, interest and experience are increasing rapidly in the use of biological systems to remove both nitrogen and phosphorus. These systems are commonly referred to as BNR systems. At the same time, many industrial wastewaters do not contain sufficient quantities of nutrients to biodegrade all of the organic matter they contain, and nutrients must be added to allow biodegradation to proceed to completion. Such additions must be balanced with the process nutrient requirements to prevent excessive quantities from being discharged into the environment.

This paper will discuss the impacts of nutrient deficiency on biological process performance, quantify nutrient requirements, and discuss methods for providing the necessary nutrients. This paper also describes the mechanisms that provide nitrogen and phosphorus removal in BNR systems, along with prototype BNR systems. It also presents resources available to wastewater treatment professionals who must consider nutrient removal options.

Nutrient Requirements

Excess quantities of nutrients are typically present in municipal wastewaters. However, the quantity of nutrients often limits the treatment of industrial wastewaters.

Impacts of Nutrient Deficiencies

A wide variety of inorganic compounds and elements are necessary components of the biomass produced in biological wastewater treatment systems. Biomass production is necessary in any biological wastewater treatment system, and when the quantity of nutrients present is not sufficient the performance of the process can be severely hampered. Adverse impacts of nutrient deficiencies include negative impacts on liquid/solids separation, such as filamentous bulking, non-filamentous bulking (exocellular polymer production), and excessive foaming (Jenkins, Richards, and Daigger 1993). In extreme cases the removal of soluble pollutants can be adversely impacted. Nitrification can be incomplete due to inadequate quantities of nutrients to produce the needed nitrifying bacteria. In more severe cases the removal of biodegradable organic matter, as reflected by the removal of soluble five-day biochemical oxygen demand (SBOD5), soluble chemical oxygen demand (SCOD), or specific organic compounds, can be adversely impacted.

Impacts on liquid/solids separation can, in turn, adversely impact plant capacity and performance. Filamentous growth occurs when nutrient concentrations are marginal since some filaments are able to consume nutrients more efficiently than the desirable floc forming bacteria when nutrients are available but at limiting concentrations. Excessive quantities of filaments result in reduced sludge settling velocities, which adversely impact secondary clarifier capacity. Exocellular polymer production occurs when insufficient quantities of nutrients are available to allow balanced growth (i.e. to allow all the biodegradable organic matter to be biodegraded and converted into biomass). Under these conditions the biodegradable organic matter present in excess of that consumed by balanced growth is converted into exocellular polymers which can interfere with sludge settling and compaction. Excessive foaming can also occur as a result of the exocellular polymers. An imbalance between mono- and di-valent cations can also negatively impact sludge settling and dewatering characteristics (Higgins and Novak 1995).

Nutrient Requirements

Nutrients must be added to biological wastewater treatment systems in proportion to the biomass produced. If the quantity of biomass which can be produced in the process is determined, nutrient requirements can be determined based on the typical nutrient content of biomass, as presented in Table 2. The quantity of biomass produced is determined by the observed yield, which is the mass of biomass volatile suspended solids (VSS) produced per unit of BOD5 or COD removed. Nutrient requirements can then be calculated using the values presented in Table 2.

Table 2. Typical Nutrient Content of Biomass

Nutrient	**Percent of Biomass**
Macronutrients	
Nitrogen[1]	10.0
Phosphorus[1]	2.0
Micronutrients	
Calcium[1]	1.5
Potassium[1]	1.5
Sodium	1.3
Magnesium[1]	0.5
Chloride	0.4
Sulfur	1.0
Iron	0.2
Manganese	0.01
Copper	0.01
Zinc	0.01

[1]Often deficient in industrial wastewater

The nutrients presented in Table 2 are divided into two categories, macronutrients and micronutrients, based on the magnitude of their requirement. The macronutrients are nitrogen and phosphorus, while the others are classified as micronutrients. As noted in Table 2, the elements nitrogen, phosphorus, calcium, potassium, and magnesium are most often found to be deficient in industrial wastewater. However, any one can limit biological growth. The residual concentrations of macronutrients must generally be greater than 1 mg/L to avoid nutrient deficiencies, while the residual concentration of micronutrients must generally be greater than 0.5 mg/L.

The typical nutrient content of biomass, as listed in Table 2, can be used to determine which nutrients are present in limited quantities. Biomass from a system suspected of being nutrient deficient can be analyzed to determine its nutrient content. Nutrients present in proportions less than those listed in Table 2 indicate that they are not present in sufficient quantities.

Nutrient Addition

If insufficient quantities of nutrients are available in the wastewater, then nutrients must be added. Several sources of the required nutrients are available, and the choice between them is based on cost, ease of handling, and availability. Typical sources of nitrogen include anhydrous ammonia, urea, and ammonium nitrate. Typical sources of phosphorus include phosphoric acid and potassium phosphate. Cations are often added as either salts (i.e. calcium chloride) or hydroxides (i.e. potassium hydroxide). The impact of the companion anion should be considered when selecting between these options. Anions are often added as salts (i.e. magnesium sulfate).

The nutrients must be added in a bioavailable form. For example, nitrogen is generally added as either NH_4^+, $N0_2^-$, or NO_3^-, while phosphorus is generally added in the ortho (PO_4^{-3}) form. Micronutrients are generally added in the soluble form. Nutrients contained in complex organic matter can become available, but they are not generally available while readily biodegradable organic matter is being metabolized. Thus, only bioavailable nutrients must be considered for readily biodegradable organic matter. Nutrient addition is particularly critical in batch or multi-staged configurations as it must be present and readily available when the biodegradable organic matter is being degraded. Nutrient additions must match requirements, to avoid overdosing. For many systems this is difficult to achieve, and special control strategies are required. It is important to recognize that physical/chemical treatment processes upstream of the biological process can remove nutrients from the wastewater and create a nutrient deficient situation.

BNR

A large number of BNR process options have been developed and used (Sedlak 1991; Randall, Barnard, and Stensel 1992; EPA 1993). Evaluation of the applicability of these processes can be confusing, particularly for those not intimately familiar with the relatively minor differences that can exist between seemingly similar process options. Differences between processes can sometimes result in significant differences in process performance and/or operational characteristics. In other cases they make little or no impact or simply represent different approaches to accomplish the same objectives. How can the practitioner distinguish between the various process options and select the one best for a particular application? The practitioner must understand the mechanisms by which nutrients are removed in biological nutrient removal processes. This allows the experienced practitioner to identify factors that determine process performance and, consequently, to determine reasonable performance differences between alternative process options.

Nitrogen Removal

Nitrogen removal occurs in any biological wastewater treatment system since nitrogen is a component of the waste biomass produced due to metabolism of biodegradable organic matter, as discussed immediately above. Organic nitrogen is also a component of the non-biodegradable particulate organic matter flocculated and removed from the process with the waste sludge. Standard procedures are available to determine the quantity of nitrogen removed by these mechanisms (Grady and Daigger, 1998; Randall, Barnard, and Stensel, 1992; Sedlak, 1991). In a BNR system, however, additional nitrogen removal is achieved by both nitrification and denitrification.

Nitrification

Nitrification is the biological conversion of ammonia-nitrogen to nitrate-nitrogen. It is accomplished by members of a group of bacteria called autotrophs. Autotrophic microorganisms oxidize inorganics to obtain energy for growth and maintenance, while they obtain carbon for the production of new biomass by the reduction of carbon dioxide. Organic matter is not required for the growth of autotrophic bacteria. Nitrification is actually a two-step reaction. The first step is the oxidation of ammonia-nitrogen to nitrite-nitrogen by bacteria of the genus *Nitrosomonas*. The second step is the oxidation of nitrite-nitrogen to nitrate-nitrogen by bacteria of the genus *Nitrobacter*. Under steady-state conditions these two reactions will be in balance and the overall reaction will go essentially to completion. Including the synthesis of new biomass (expressed as the typical composition of biomass), the overall reaction is:

$$NH^{+}_{4} + 1.83\ O_2 + 1.98\ HCO^{-}_{3}\ \varsigma\ 0.98\ NO^{-}_{3} + 0.021\ C_5H_7NO_2 + 1.88\ H_2CO_3 + 1.04\ H_2O$$

From Eq (1) 4.6 mg of O_2 is required for each mg of $N0_3$-N produced. Bicarbonate alkalinity is consumed to neutralize the acid produced (i.e. ammonia-nitrogen is a base while nitrate-nitrogen is an acid) and for the synthesis of new biomass (from carbon dioxide, which is present as bicarbonate alkalinity). The alkalinity requirement is 7.2 mg of alkalinity as $CaCO_3$ for each mg of $N0_3$-N produced. Biomass yield values are typically low for autotrophic bacteria, and nitrification is no exception, with a value (including both *Nitrosomonas* and *Nitrobacter*) of 0.15 mg as total suspended solids (TSS) per mg of $N0_3$-N produced.

The growth of nitrifying bacteria is affected by a number of factors (EPA 1993). The nitrifier maximum specific growth rate is generally lower than that of the heterotrophic bacteria that oxidize biodegradable organic matter. This is often characterized as the minimum solids residence time (SRT_{min}), which corresponds to the maximum specific growth rate for the subject microorganisms. When the process is operated at SRT_{min}, the microorganisms are growing at their maximum rate and are just being washed out of the system. The SRT must be longer than SRT_{min} if the organisms are to grow and survive in the system. The SRT where nitrification occurs in the system is typically 1.5 to 2.0 times $SRT_{min.}$ Figure 1 presents SRT_{min} for the nitrifying bacteria as a function of temperature and illustrates their temperature sensitivity.

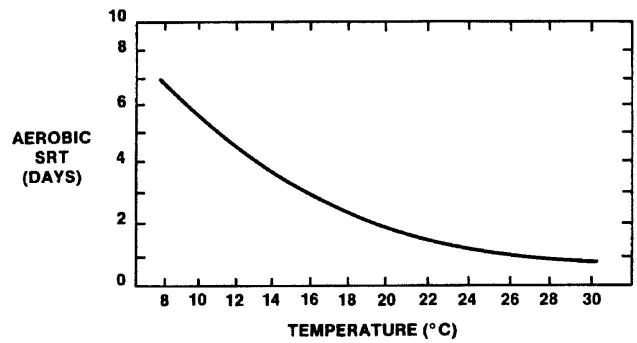

Figure 1. Variation in Nitrifier SRT_{min} with Temperature

Additional factors affecting growth of nitrifying bacteria include DO, pH, and the presence of inhibitors. As illustrated in equation (1), nitrification is an aerobic reaction. The activity of the nitrifying bacteria is reduced when the DO concentration is reduced below about 2 to 3 mg/L, and it is totally inhibited when DO is not being supplied. Nitrification can occur when DO is being supplied but DO concentrations are low; however the rate is reduced. The optimum pH for growth of the nitrifying bacteria is about 7.5. Their activity is reduced somewhat at pHs below 7.0, and it is inhibited significantly at pHs below 6.5. Recent information distinguishes between the impact of pH on acclimated and unacclimated cultures (EPA, 1993). A wide variety of organic and inorganic compounds can also inhibit the growth of the nitrifying bacteria. This can be an important issue when certain industrial wastewaters are being treated, particularly for chemical processing, petrochemical, or wastewaters containing elevated heavy metal concentrations (EPA, 1993; Sedlak,1991). Procedures are available to determine the SRT_{min} in the presence of nitrification inhibitors (Sadick, et al., 1995).

Denitrification

Denitrification is utilization of biodegradable organic matter by heterotrophic bacteria using nitrate-nitrogen as the terminal electron acceptor (i.e. the “oxygen source”). Many heterotrophic bacteria in biological wastewater treatment systems can use either DO or nitrate-nitrogen as a terminal electron acceptor. DO is used preferentially when both are present since somewhat more energy can be obtained from it. However, DO and nitrate-nitrogen provide essentially the same biochemical function. When nitrate-nitrogen serves as the terminal electron acceptor (i.e. denitrification occurs), nitrate-nitrogen is converted to nitrogen gas. Nitrogen removal occurs when the nitrogen gas is liberated into the atmosphere.

Denitrification significantly impacts the stoichiometry of a biological wastewater treatment system. Since a portion of the carbonaceous oxygen demand is satisfied by the reduction of nitrate-nitrogen, the process oxygen demands are reduced. Theoretically, 2.86 mg of biodegradable oxygen demand is satisfied for each mg of $N0_3$-N reduced to nitrogen gas. Denitrification also results in reduced process alkalinity consumption due to the removal of the acid nitrate. Theoretically, 3.6 mg of alkalinity as CaCO3 is produced per mg of $N0_3$-N reduced to nitrogen gas. Table 3 illustrates the complementary nature of the nitrification and denitrification reactions.

Table 3. Nitrification/Denitrification Process Stoichiometry

Component	**Nitrification**	**Denitrification**
Oxygen (mg O_2/mg NO_3-N)	4.6 Consumed	2.86 Demand Satisfied
Alkalinity (mg as $CaCO_3$/mg NO_3-N)	7.2 Consumed	3.6 Produced

As illustrated in Figure 2, for many wastewaters the denitrification rate varies over a wide range as different fractions of organic matter are oxidized. Initially, a relatively high denitrification rate occurs as the readily biodegradable organic matter is oxidized. The denitrification rate is reduced when the more slowly biodegradable organic matter is oxidized. Finally, when all the biodegradable organic matter is oxidized the denitrification rate is relatively low and is driven only by endogenous respiration. If the organic matter in the influent wastewater is to be used as the primary carbon source, it must be used effectively if a relatively high degree of denitrification is to be achieved. This is accomplished by process configurations that use the influent wastewater first for denitrification, as discussed below.

Prototype System

Figure 3 illustrates a prototype single sludge biological nitrification/denitrification process known as the four-stage Bardenpho process. It consists of two anoxic zones and two aerobic zones. An anoxic zone is a region where DO is excluded and $N0_3$-N is provided as the terminal electron acceptor. Denitrification occurs in anoxic zones. An aerobic zone is aerated to provide DO as the terminal electron acceptor. Both the oxidation of biodegradable organic matter and nitrification occur in the aerobic zone. In Figure 3, nitrification (the first step in biological nitrogen removal) occurs in the first aerobic zone. Denitrification (the second step) occurs in the first and second anoxic zones. $N0_3$-N is provided to the first anoxic zone by the mixed liquor recycle stream. The mixed liquor flowing from the first aerobic zone to the second anoxic zone will contain the $N0_3$-N necessary. The second aerobic zone is relatively small and is used simply to freshen the mixed liquor and physically strip nitrogen gas bubbles from the mixed liquor before it flows into the clarifier. Table 4 summarizes the functions of the various components of the four-stage Bardenpho process.

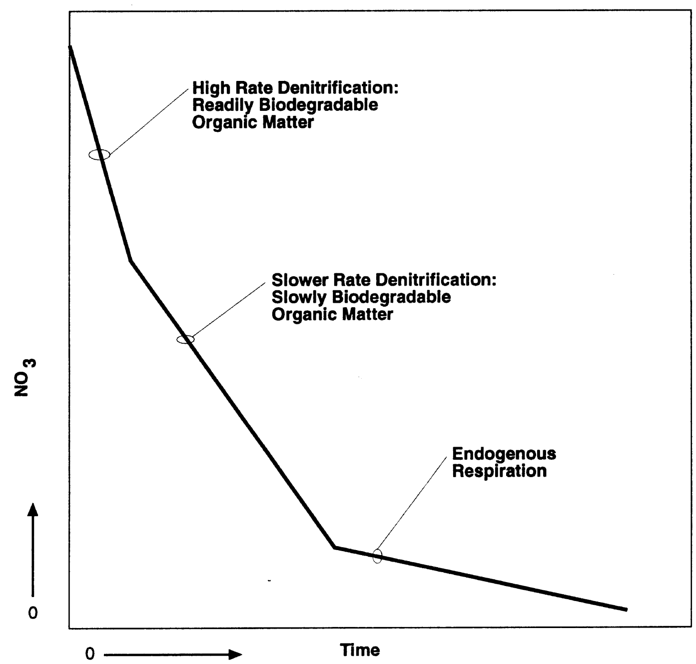

Figure 2. Wastewater Fractions Produce Different Denitrification Rates

Factors affecting the performance of biological nitrogen removal processes are listed in Table 5. Wastewater characteristics affect process performance due to stoichiometric relationships between biodegradable organic matter and the $N0_3$-N to be denitrified. As discussed above, theoretically 2.86 mg of carbonaceous oxygen demand must be oxidized to denitrify 1 mg of $N0_3$-N. Practically, the quantity of biodegradable organic matter must exceed the theoretical requirement since not all of it can be denitrified. The wastewater 5-day biochemical oxygen demand (BOD_5) to total Kjeldahl nitrogen (TKN) ratio (BOD_5/TKN) must exceed four if reasonably complete denitrification is to be achieved. Higher values lead to even more complete denitrification. The biodegradability of the wastewater, that is, the proportion of the organic matter that is readily biodegradable, also affects the size and performance of the process. If the readily biodegradable organic matter concentration is relatively high, the rate of denitrification will be high and process performance will be enhanced.

The sizes of the various zones will affect performance. The first aerobic zone must be sized for a relatively high degree of nitrification. The process SRT calculated based on only the inventory in this zone (known as the aerobic SRT) determines the degree of nitrification. It must exceed SRT_{min} for the nitrifiers (as presented in Figure 1) for nitrification to occur. As discussed above, the aerobic SRT must be 1.5 to 2.0 times SRT_{min}, or more.

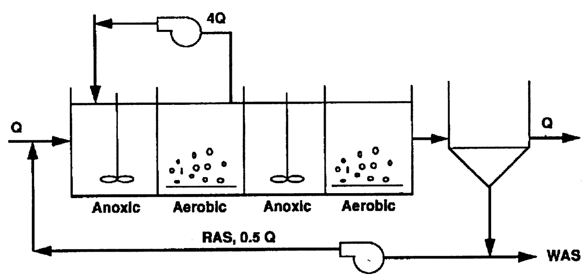

Figure 3. Prototype Single Sludge Biological Nitrogen Removal Process

Table 4. Functions of Bardenpho Process Components

Component	**Function**
First Anoxic Zone	High-Rate Denitrification, Driven by Process Influent Organic Matter
First Aerobic Zone	Nitrification
Second Anoxic Zone	Low Rate Denitrification, Driven by Endogenous Respiration
Second Aerobic Zone	Stripping of Nitrogen Gas, Addition of Dissolved Oxygen to Mixed Liquor
Mixed Liquor Recycle	Transport of NO3-N Generated in the First Aerobic Zone to the First Anoxic Zone

Table 5. Factors Affecting Biological Nitrogen Removal

Wastewater	Configuraton
• BOD_5/TKN	Γ Zone Size and Loading
• Biodegradability	Γ Aeration System Configuration and Operation
• Temperature	Γ Mixed Liquor Recycle Rate
• Inert Content	
• Variability in Characteristics	

Denitrification in the first anoxic zone is a function of the size of the zone, the mass of $N0_3$-N recycled to it, and the rate at which organic matter is biodegraded. The mass of $N0_3$-N recycled is a direct function of the mixed liquor recycle flow rate. As illustrated in Figure 4, an increase in this rate increases the mass of $N0_3$-N recycled and the percent $N0_3$-N removal possible. Increased recycle rates can also lead to diminishing returns. This occurs because the mass of $N0_3$-N recycled is a function of both the first aerobic zone effluent nitrate-nitrogen concentration and the recycle flow rate. An increase in the recycle flow rate increases the recycled mass, but at a diminishing rate because the first aerobic zone $N0_3$-N concentration decreases due to increased denitrification. The following equation can be used to calculate the denitrification potential as a function of the mixed liquor recycle rate (expressed as a percentage of the process influent flow rate, R).

$$\text{percent } Denite \left[\frac{R}{\Gamma + R} \right] 100$$

Several approaches are available to estimate the specific rate of denitrification in both the first and second anoxic zones. A frequently used correlation is that developed by Burdick, Stensel, and Refling (1982). When a detailed wastewater characterization is available, sophisticated process models such as that developed by the South Africa Water Research Commission (Water Research Commission 1984) or the International Association on Water Quality (IAWQ, formerly known as the International Association on Water Pollution Research and Control) Activated Sludge Model Number 1 (ASM 1) (Henze, et al. 1987) can be used. These models accurately characterize full-scale biological nitrogen removal facilities when properly calibrated. The reader is referred elsewhere for more details (Grady and Daigger 1998; Daigger and Grady1995; EPA 1993).

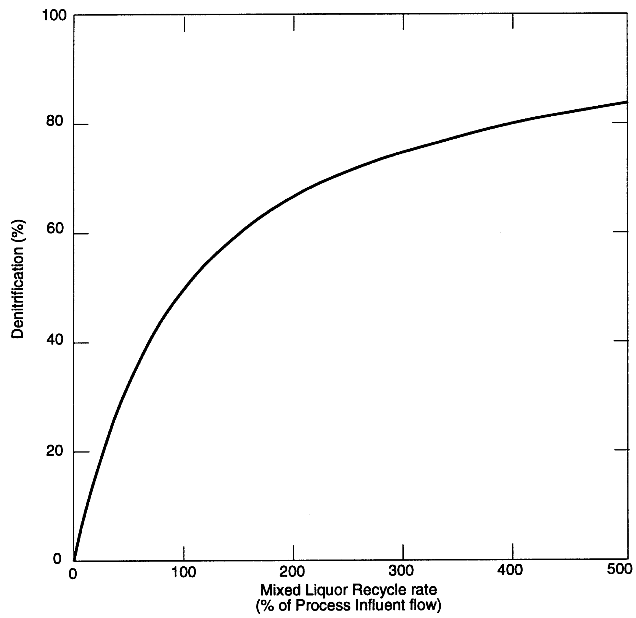

Figure 4. Denitrification as a Function of Mixed Liquor Recycle Rate

Other Systems

A large number of other process options are available. When a lesser degree of nitrogen removal is acceptable, a system consisting of only the first anoxic zone, the aerobic zone, and the mixed liquor recycle stream may be adequate. Other systems obtain nitrogen removal through the phenomenon known as simultaneous nitrification/denitrification. Nitrification and denitrification do not actually occur at the same time since different environmental conditions are required. However, nitrification and denitrification can occur in different portions of an aerated basin. This occurs by two mechanisms. First, both aerobic and anoxic zones can exist within an aerated basin due to the nonuniform conditions which exist in full-scale aeration basins. Second, anoxic zones can develop inside activated sludge flocs, even in aerated systems. Both mechanisms operate to some extent in any aeration basin. Many systems exist that exploit this feature to encourage an extensive degree of nitrification and denitrification. In these systems, the aeration rate must be carefully controlled so that the oxygen transferred just equals that needed to oxidize the carbonaceous organic matter and to nitrify the applied ammonia-nitrogen loadings, including the credit for denitrification. Table 6 summarizes several biological nitrogen removal systems.

Table 6. Other Example Biological Nitrogen Removal Processes

- Oxidation Ditch
- Sequencing Batch Reactor
- Intermittent (Cyclic) Aeration Systems
- Schreiber Process
- Nonuniform Aeration

Phosphorus Removal

Phosphorus removal occurs in a biological system by the accumulation of phosphorus in the process mixed liquor and removal of the accumulated phosphorus in the waste activated sludge (WAS). Increased accumulation of phosphorus occurs due to the selection of high phosphorus content microorganisms. The phosphorus content of these phosphorus accumulating organisms (PAOs) can approach 35 percent on a phosphorus to volatile suspended solids (VSS) basis (Wentzel 1988), which significantly exceeds the phosphorus content of typical biomass (Table 1). Depending on the proportion of the PAOs in the process mixed liquor, the phosphorus content of the activated sludge mixed liquor can be increased from about 2 percent (P/VSS) for conventional activated sludge systems up to typical values in the 6 to 8 percent range, and as high as 14 percent or more, for biological phosphorus removal systems. Phosphorus is a conservative substance, so the mass of phosphorus in the process influent must equal the mass of phosphorus in the process effluents (both the liquid effluent and the WAS). In a biological phosphorus removal system, increased removal of phosphorus from the process influent is accomplished by increasing the mass of phosphorus in the WAS. Then, due to conservation of mass, a lower mass (and therefore lower concentration) of phosphorus will be present in the process effluent.

Organism Selection Mechanism

What factors are responsible for the growth of these PAO in biological phosphorus removal systems? They are selected by cycling mixed liquor between anaerobic and aerobic environments. To understand this statement, it is first necessary to define the term anaerobic. In biological nutrient removal systems, anaerobic is defined as the absence of both DO and $N0_3$-N as terminal electron acceptors. Under these conditions, the capability of heterotrophic microorganisms to metabolize biodegradable organic matter is dramatically reduced. Since no terminal electron acceptor is available, organic matter cannot be oxidized to generate energy. Fermentative reactions (the oxidation of one organic compound by another) can occur, but these reactions result in only limited production of energy. In contrast, the PAOs transport soluble organic matter across the cell membrane and store it under anaerobic conditions. They are able to do this using energy stored in the form of high energy phosphate-to-phosphate bonds.

The PAOs contain high concentrations of polyphosphate, a polymer in which individual phosphate molecules are linked by high energy bonds. Energy released by cleavage of these bonds is used to transport organic matter into the cell and store it, as illustrated in Figure 5. The phosphate produced by cleavage of the high energy phosphate-to-phosphate bonds diffuses out of the cell, resulting in an increase in soluble phosphate concentration. When the PAOs subsequently pass into the aerobic zone, oxygen is provided to allow aerobic metabolism. As illustrated in Figure 5, the PAOs then oxidize the stored organic matter and generate energy used to take up phosphate from solution and store it as polyphosphate.

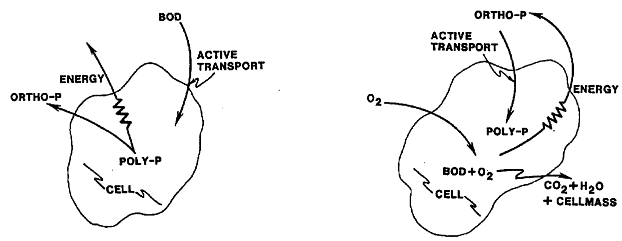

Figure 5. Phosphorous and Organic Matter Cycling in Biological Phosphorous Removal System

Polyphosphate in the PAOs has been characterized as a “battery” that stores chemical energy for use as needed. The battery is discharged in the anaerobic zone to provide the energy necessary to transport and store soluble organic matter. It is then recharged in the aerobic zone as the stored organic matter is oxidized to generate energy. This characterization, although simplified, is accurate. The stored polyphosphate is also responsible for the high phosphorus content of the PAOs. Consequently, any factor that encourages the metabolic pattern described above also improves phosphorus removal.

<u>Prototype System</u>

Figure 6 illustrates the basic configuration of a biological phosphorus removal system. It consists of an initial anaerobic zone which receives return activated sludge (RAS) from the clarifier and the process influent wastewater. Uptake of soluble organic matter occurs in this zone, along with the corresponding release of phosphate. The mixed liquor then flows out of the anaerobic zone and into the aerobic zone where organic matter is oxidized and phosphate uptake occurs. The PAOs grow relatively slowly (but generally faster than the nitrifying bacteria). Both laboratory and full-scale experience indicates that a minimum process SRT on the order of three days must be maintained to avoid PAO washout (Mamais and Jenkins, 1992). The hydraulic residence time in the anaerobic zone is typically 0.75 to 1.0 hour based on the process influent flow rate. Additional discussion of factors affecting the required anaerobic zone HRT is provided below.

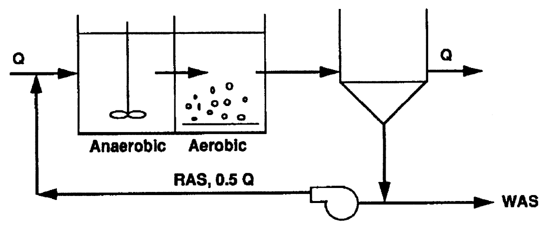

Figure 6. Prototype Biological Phosphorus Removal Process

The process configuration presented in Figure 6 is the simplest biological phosphorus removal process, and it is quite appropriate and effective when nitrification is not required or desired. However, in such a configuration biological phosphorus removal is adversely affected if the aerobic zone is large enough to allow nitrifying bacteria to grow. This occurs because nitrification results in the production of $N0_3$-N, which is recycled to the anaerobic zone in the RAS. This $N0_3$-N recycle provides a terminal electron acceptor in the initial mixed zone that allows heterotrophic denitrifying bacteria to compete with the PAOs for organic matter. Under these circumstances, a reduced competitive advantage is provided for the PAOs, resulting in reduced enrichment of the population with PAOs and reduced biological phosphorus removal. As a consequence, a variety of process configurations have been developed that restrict the recycle of $N0_3$-N to an aerobic zone in nitrifying systems.

<u>Other Systems</u>

One such system is the Virginia Initiative Plant (VIP) process, illustrated in Figure 7. It consists of an initial anaerobic zone to select PAOs, an anoxic zone with mixed liquor recycle for denitrification (resulting in total nitrogen removal), and anaerobic zone for nitrification and phosphorus uptake. RAS (which will contain $N0_3$-N) is directed to the anoxic zone where denitrification occurs. An additional in-process recycle stream is introduced as the anoxic recycle (ARCY), which takes denitrified mixed liquor exiting the anoxic zone and delivers it to the process influent as it flows into the anaerobic zone. This recycle stream is necessary to deliver mixed liquor into the anaerobic zone to allow biological reactions to occur. Because a denitrified mixed liquor is recycled, $N0_3$-N addition to the anaerobic zone is minimized, thereby minimizing the interference of nitrate-nitrogen with biological phosphorus removal. As a consequence, the biological phosphorus removal capability of the process is maximized.

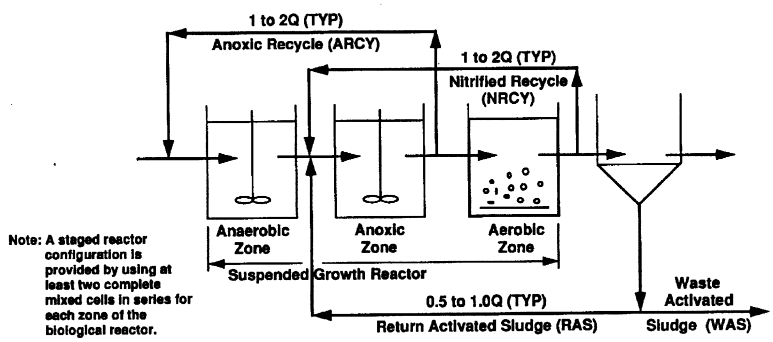

Figure 7. VIP Process

As discussed above, the nature of the organic matter added to a biological nutrient removal process affects nitrogen removal. This is also true for biological phosphorus removal because of the highly specialized requirements of the PAOs. As discussed above, in the anaerobic zone the PAOs transport soluble organic matter across the cell membrane and store it as intracellular carbon storage products. In fact, these microorganisms only transport and store low molecular weight volatile fatty acids (VFAs) such as acetic and propionic acid (Randall, Barnard, and Stensel 1992). Consequently, the mass of VFAs available to these microorganisms dramatically affects the performance of biological phosphorus removal systems. Some wastewaters have sufficient concentrations of VFAs present, in many cases due to fermentative reactions occurring in the collection system. In many instances, however, this is not the case, and biodegradable organic matter must be fermented to generate the necessary VFAs.

Several approaches are available to generate the VFAs. The two discussed here are fermentation of readily biodegradable organic matter in the anaerobic zone of the biological phosphorus removal process and the fermentation of particulate matter in a separate fermenter. In any biological phosphorus removal process, a portion of the readily biodegradable organic matter (as defined and described above under the discussion of biological nitrogen removal) will be fermented in the anaerobic zone to produce VFAs. This occurs because many of the heterotrophic microorganisms in biological wastewater treatment systems have fermentative capabilities. By definition, the readily biodegradable organic matter is available to the microorganisms for biological reaction. In an anaerobic environment, where the readily biodegradable organic matter cannot be oxidized due to the absence of a terminal electron acceptor, it will be fermented to produce VFAs and other fermentation products.

The uptake of VFAs is a relatively rapid reaction, requiring an anaerobic zone SRT as short as 0.3 to 0.5 days. For many processes this corresponds to an anaerobic zone hydraulic residence time (HRT, computed based on the process influent flow rate) of 0.75

hour or less. The fermentation of readily biodegradable organic matter is a slower process, generally requiring an anaerobic zone SRT of 1.5 to 2 days. This corresponds to an anaerobic zone HRT of 1 to 2 hours or more. This provides guidance on the required anaerobic zone HRT for a particular application. If the influent wastewater contains significant concentrations of pre-formed VFAs, a relatively short anaerobic zone SRT and HRT can be used. If, on the other hand, significant fermentation is required in the anaerobic zone to generate VFAs, then a longer anaerobic zone SRT and HRT will be required. Also note that the recycle of $N0_3$-N to the anaerobic zone will interfere with fermentation reactions. Given the option of either using nitrate-nitrogen to oxidize readily biodegradable organic matter or fermenting the readily biodegradable organic matter, oxidation using nitrate-nitrogen will dominate due to the greater amount of energy the microorganisms can obtain through oxidative reactions. This is another reason that the recycle of nitrate-nitrogen to the anaerobic zone can interfere with effective and efficient biological phosphorus removal.

The fermentation of particulate biodegradable organic matter is a relatively slow reaction that must generally be accomplished external to the biological nutrient removal process. Figure 8 illustrates a typical approach that involves the addition of primary sludge (PSD) to a mixed reactor where the particulate matter is fermented to generate VFAs (Skalsky, et al. 1992). This reaction generally takes 2 to 3 days. The fermented primary sludge is then sent to a liquid/solids separation device such as a gravity thickener. In some instances an elutriation flow such as primary effluent (PE) is added to "wash" the soluble VFAs from the remaining particulate matter. The overflow, which contains high concentrations of VFAs, is directed to the anaerobic zone of the biological nutrient removal process while the underflow containing the remaining particulate matter is sent to sludge treatment. Several primary sludge fermentation configurations are available and are used in full-scale applications (Grady and Daigger 1998).

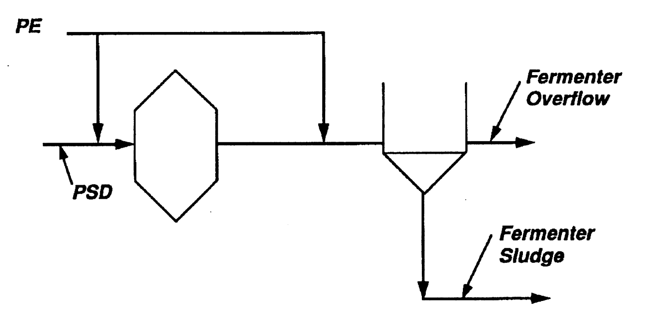

Figure 8. Example Fermentation Process

A wide variety of biological phosphorus or biological nitrogen and phosphorus removal process options are available, each with their own advantages and disadvantages. Table 7 summarizes several of these. These processes are described in detail in the references discussed below.

Table 7. Other Example Biological Phosphorus Removal Processes

- A^2/O
- Five stage Bardenpho
- University of Capetown (UCT)
- Johannesburg (JHB)
- OWASA

Available Resources

A number of good resources are available to assist those interested in learning more about biological nutrient removal systems. Table 8 provides a list of key references that the beginner will find useful in gaining an overall perspective on biological nutrient removal processes. Additional information is presented in the references at the end of the paper. Individual references contained within the key references can provide the more advanced user with the detailed information needed for a more in-depth understanding of BNR systems. Knowledge concerning the design and operation of BNR systems is advancing rapidly. Consequently, the interested user is cautioned to review the current literature to follow the introduction and evaluation of new BNR system concepts.

Table 8. Key References

- Phosphorus and Nitrogen Removal from Municipal Wastewater: Principles and Practice, 1991.
- Process Design Manual for Nitrogen Control, 1993.
- Theory, Design, and Operation of Nutrient Removal Activated Sludge Processes, 1984.
- Nutrient Control, WPCF, 1983.
- Design and Retrofit of Wastewater Treatment Plants for Biological Nutrient Removal, 1992.

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Update on Rhode Island Department of Environmental Management Activities Related to Nutrients and Narragansett Bay

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Rhode Island Department of Environmental Management

Monitoring

In recent years, monitoring efforts beyond the shellfish bacterial monitoring in the bay have been limited to select subareas of Narragansett Bay based on limited, area-specific grant funding. However, thanks to seed money provided to RI DEM by Sen. John Chafee of the Rhode Island Congressional delegation, a multi-partner baywide monitoring system has been developed. A grant totaling $1.5 million for monitoring work on Narragansett Bay and other Rhode Island marine waters is providing the first steps towards a comprehensive continuous monitoring system.

The comprehensive monitoring system being assembled is a collaborative effort with RI DEM Division of Fish & Wildlife (F&W), Office of Water Resources (OWR), and the Narragansett Bay Estuary Program (NBP); NOAA National Marine Fisheries Service (NMFS); the U.S. Environmental Protection Agency (EPA) Atlantic Ecology Division Lab; the National Estuarine Research Reserve at Prudence Island (NERR) the University of Rhode Island (URI); and Roger Williams University.

The in-bay components of the monitoring system include at least 3 major efforts:

1. A monthly survey of the zooplankton in the bay by NOAA/NMFS scientists using an advanced computer-controlled shuttle towed behind a boat. The device can undulate up and down the water column, sampling zooplankton while simultaneously measuring depth, salinity, temperature, dissolved oxygen (DO), pH, and chlorophyll a as a tow boat covers set transects of the bay. The present transect layout covers the Providence River, upper bay, the East and West passages, and part of Mount Hope Bay and Greenwich Bay. Chlorophyll a is being measured with a state-of-the-art "flash" fluorometer.

2. Continuous water quality monitoring stations at seven sites strategically selected around the bay to provide a good picture of the overall health of the bay. These stations will have two or three continuous monitoring probes set at several depths measuring salinity, temperature, DO, pH, tide height, and, for selected stations, turbidity and/or chlorophyll a. Narragansett NERR, RI DEM, and URI "own" specific station probe equipment (Endico/YSI systems) mounted at the sites or buoys. URI and Roger Williams University maintain the equipment.

3. Surface sediment samples and analyses for trace metals and organics were taken in 1997-98 at 43 stations scattered around the bay, and three (1 m) cores were taken at

three sites. At least 20 stations previously sampled (1988-89) for the original NBP-funded bay characterization study were sampled for this effort to allow for data comparisons/trend analyses. The recent surface sediment concentrations reflect an integration of changes in loadings of the various pollutants analyzed over the last decade.

Much of the water column monitoring for this comprehensive effort is concentrated on issues related to excess nutrients and their impacts, including low DO. Sediment samples were taken in 1997 and 1998, with chemical analyses completed in late 1998, while four of the water column continuous monitoring probe stations have become operational (1998-99), and the other three are expected on-line by summer 1999. Monthly transect sampling cruises of the zooplankton in the bay have been ongoing since February 1998.

The data for this monitoring system will eventually be posted and available to the public on the World Wide Web through the data center at the URI Graduate School of Oceanography. A voluntary effort scheduled for the summer of 1999 has also been organized to measure overnight decreases in DO across the entire upper half of Narragansett Bay using Rapid Response "SWAT" boat teams to cover large areas of the bay simultaneously. This effort includes volunteers from the EPA Atlantic Ecology Division Lab, Narragansett Bay Commission, RI DEM, U.S. Fish and Wildlife, URI, Save The bay, and others.

The goal of the NBEP survey is to begin first steps towards mapping a sporadic hypoxic zone that appears to be developing at least once every two years in the upper bay under specific meteorological conditions. The ultimate goal of all of these investigations is to provide data useful to the state to use in developing the total maximum daily load (TMDL) for nutrients, especially N, in the Providence/Seekonk Rivers.

Permitting

DEM point source permit staff are now including language in permits upon reissuance indicating that nitrogen criteria will likely be coming in the future and all major facilities should include denitrification in their facilities plans. In fact, following this workshop, several municipalities have agreed to attempt using the revised operational treatment procedures to increase the level of denitrification as was seen in Connecticut. The loading decreases are projected for the plants to potentially exceed 50 percent, dropping from levels of 18 to 30 mg/l total nitrogen to 7 to 8 mg/l total nitrogen.