NUTRIENT CRITERIA STRATEGY FOR THE TIDAL AND NON-TIDAL DELAWARE RIVER

Delaware River Basin Commission
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DELAWARE RIVER BASIN COMMISSION
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This report was prepared by the Delaware River Basin Commission staff: Carol R. Collier, Executive Director. Edward D. Santoro and Robert L. Limbeck were the principal authors of this report. DRBC staff also contributing to this report included John Yagecic, Dr. Namsoo S. Suk, Dr. Thomas Fikslin, Dr. Erik Silldorff, and Dr. Ronald MacGillivray.

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NUTRIENT CRITERIA STRATEGY FOR THE TIDAL DELAWARE RIVER ESTUARY

Introduction

In 1998, the U.S. EPA released a Water Quality Standards and Criteria Plan (U.S. EPA 1998a) expressing the need for development of regional numeric criteria for nutrients. A companion document entitled the National Strategy for the Development of Regional Nutrient Criteria (U.S. EPA 1998b) outlined the approach that EPA would take in establishing recommended criteria and working with states to get numeric criteria adopted into state water quality standards. EPA subsequently published Water Quality Criteria Recommendations documents containing proposed nationwide criteria for 14 Aggregate Nutrient Ecoregions. Of the 14 nationwide nutrient ecoregions, five are located in the Delaware River Basin (U.S. EPA 2000a, 2000b, 2000c, 2000d, 2001a). To assist states in refinement of ecoregional criteria, EPA also published technical guidance documents for rivers/streams (U.S. EPA 2000e) and for coastal and estuarine waters (U.S. EPA 2001b). The guidance documents describe the process by which nutrient criteria could be developed.

The U.S. EPA has directed states to submit nutrient criteria development strategies. Such strategies could be as simple as accepting the U.S. EPA recommended nutrient ecoregional criteria, which were based upon adoption of the 25th percentile of historically reported total nitrogen, total phosphorus and other constituent concentrations as numeric reference criteria. Basin states are currently developing/refining nutrient criteria strategies. The Delaware River Basin Commission is also committed to developing a strategy for the tidal and non-tidal interstate waters of the Basin

There are several reasons why the Delaware River Basin Commission elects to examine nutrient criteria in greater detail using more lines of scientific evidence. First, none of the DRBC member states accepted ecoregional nutrient criteria for their water quality rulemaking, but elected to develop their own nutrient criteria strategies. Second, DRBC examined the recommended criteria for the 5 aggregate ecoregions through which the Delaware River flows. From upstream to downstream, the Delaware River is contained within aggregate nutrient ecoregions VII, VIII, XI, IX, and XIV. Recommended total phosphorus concentrations begin at 33 µg/l, and jump down to 10, 10, then up to 37, and 31 µg/l, respectively, from the headwaters to the mouth of the bay. Similarly, recommended total nitrogen concentrations begin at 0.54 mg/l and jump down to 0.38, 0.31, up to 0.69 and 0.71 mg/l, respectively. Implementation of such criteria would be difficult, especially since riverine and estuarine concentrations are largely much higher than the recommended reference criteria, yet do not seem to cause obvious eutrophication effects. Third, the national nutrient ecoregional recommendations used data that were not specific to the Delaware River and Bay, and the DRBC recommends using local data for local criteria. Fourth, it would be appropriate to consider multiple lines of evidence in the development of such significant criteria. Therefore, this strategy employs local information and a weight-of-evidence approach to nutrient criteria that begins with the percentile or reference approach (but based only on local data) and is eventually tied to additional lines of evidence such as aquatic life, drinking water and recreation effect-levels; and results of eutrophication modeling of the Delaware River and Bay.

The goal of this strategy is to identify the specific steps that the Delaware River Basin Commission (DRBC) will use to establish water quality criteria for the control of nutrient enrichment for the tidal and non-tidal portions of the system. Initially, nutrient standards will be developed for the estuary to provide a benchmark for maintenance of existing water quality. In the non-tidal river, the Commission's Special Protection Water regulations already require no measurable change to existing water quality. To further refine the criteria, innovative procedures will evaluate the utility of biological standards based upon nutrient effects and estimate the potential effects of nutrient additions upon aquatic organisms in the system.

There are four basic principles of DRBC's approach.

1). The setting of nutrient criteria in the tidal river and bay uses a large data set (> 17 years) from the Commission's long-term boat run program and river studies.

2). Most of the main stem Delaware River is currently meeting fishable water quality objectives associated with eutrophic effects, where designated. Also in the tidal and non-tidal freshwater portions of the river, drinking water intakes exist which could be impacted by phytoplankton that contribute to taste and odor problems in those areas. Since the early 1990's, the Delaware River and Bay have not exhibited obvious signs of eutrophication i.e.; anoxia, fish kills, algal blooms or water discoloration. Elevated nutrient levels are effectively utilized by resources downstream.

3). The DRBC currently is proposing to maintain existing water quality as the basis for nutrient criteria in the estuary. However, DRBC will also evaluate other approaches for establishing nutrient criteria.

4). DRBC will continue to evaluate the impacts that excessive levels of nutrients may have upon the aquatic organisms in the Delaware River Basin. Current efforts include nutrient impact thresholds and algal stimulation studies in the freshwater portions of the main stem river.

The goal of this strategy is to identify the steps that the Delaware River Basin Commission (DRBC) will use to establish water quality standards for nutrients for the tidal and non-tidal portions of the system. In developing these standards, it is anticipated that the tools developed by each of the basin states will be evaluated for suitability of use within the shared basin waters. For the estuary, achieving the nutrient standards will provide a benchmark for assessment of future levels. In the non-tidal areas, innovative procedures will provide tools to estimate the potential effects upon aquatic organisms in the system, provide estimates of tributary loadings of nutrients into the system, and ascertain significant sources of these materials.

BACKGROUND-DELAWARE ESTUARY

The Delaware Estuary receives inputs of nutrients primarily from urban and industrial sources. The main stem waters between Burlington, New Jersey, and Wilmington, Delaware, were estimated to have the highest concentrations of nitrogen of any major estuary in the United States

(Sharp 1994). Approximately 50% of the inorganic nitrogen and 80% of the phosphate entering the estuary results from human activity. The Delaware estuary has not exhibited obvious signs of eutrophication. This is likely due to several factors such as high turbidity and rapid movement of the water mass out of the system. The turbidity maximum varies depending upon river inflow but typically occurs approximately 78 miles from the mouth of Delaware Bay near Marcus Hook PA. The flushing time for water mass in the system is rapid, typically 90 – 120 days. From the 1960's to the late 1980's large increases in dissolved oxygen concentrations and a large reduction in phosphorus loadings have occurred. Over that period there has been little or no change in suspended solids and total nitrogen levels. Currently, the minimum oxygen levels are typically above 4.5 mg/l in the main stem river.

The DRBC boat run program measures nutrient concentrations, algal biomass and primary productivity which are useful to determine the river's trophic status. Nutrients, especially phosphorous in fresh waters, are a link to increased algal biomass, although physical constraints, such as light, temperature, and current can determine the potential for nutrient utilization by algae and aquatic plants. Chlorophyll-a, a green pigment utilized by algae and green plants during photosynthesis to convert light, carbon dioxide, and water to sugar, is commonly used as an index of algal biomass. The relative concentration of chlorophyll a can also be used to assess phytoplankton growth.

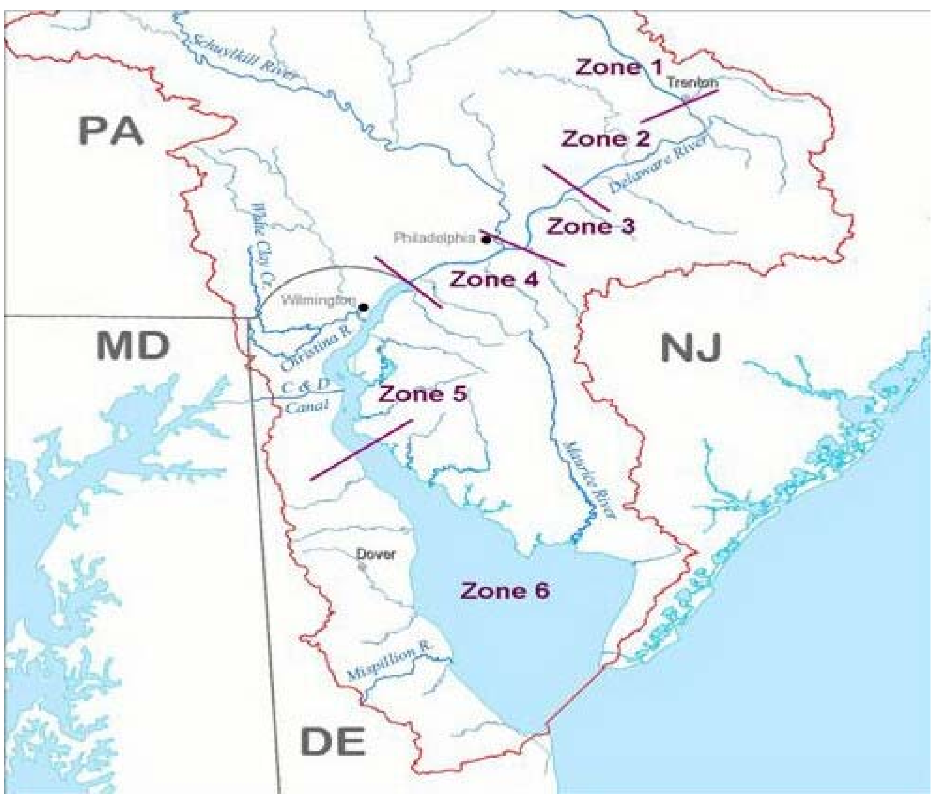


Figure 1: Map Showing the Water Quality Zones in the Delaware Estuary.

Santoro (2000) documented a dramatic increase in nutrient loading to the Delaware Estuary since the early 1900s, associated with dramatic population growth during the first half of the century. That report also noted, however, that high nutrient concentrations have not had significant eutrophic effects in the estuary. The Delaware Estuary has been characterized as a nutrient-rich system, containing some of the highest levels of nitrogen and phosphorus of any of the world's estuaries (Sharp 1988).

As a benchmark for nutrient levels in the Delaware Estuary, it is helpful to look at corresponding levels in the Chesapeake Bay, where eutrophication has been a major concern triggering regulatory action. C.F. Cerco and T. Cole, who developed a three-dimensional eutrophication model for the Chesapeake, observed chlorophyll a values of 10 to 25 mg/l; nitrate and nitrite values of 0.0 to 0.75 mg/l; and total phosphorous values of 3.5 to 16 mg/l (Cerco & Cole, 1993). In the Delaware Estuary, mean chlorophyll values are similar, as are mean nitrite values. Mean nitrate values, at between 1 and 2 mg/l with exceptions at the top and bottom of the estuary, are somewhat higher than in the Chesapeake Bay; and total phosphorous values are considerably lower, ranging from 0.00 to 0.97 mg/l. Although nutrient concentrations are comparable to Chesapeake Bay, no obvious eutrophic effects are noted in the Delaware Estuary.

Depth Related Effects

The only depth related data available for nutrients was that collected in 1997 during the MAIA program, and the National Coastal Assessment Program in 2000 through 2006. This data was collected once at each of the 92 stations in the Delaware Estuary in 1997 and at 35 to 25 stations at each of the other years. The program sampled bottom, mid and surface levels for different nutrient parameters. The results of this data set suggest Delaware River is a well mixed body of water, with the surface and bottom nutrient levels generally similar.

Inflow Effects

The Delaware Estuary is dominated by freshwater flow from the Delaware River. Various water-quality parameters (nutrients, total suspended solids, etc.) and the degree of stratifications in the estuary are influenced by the seasonal discharge pattern of the Delaware River (Sharp et al. 1986). This flow, and the nutrients and suspended solids it contains will affect the abundance and productivity of phytoplankton throughout the year (Pennock 1985). Sharp et al. (1986) have shown a direct relationship between a high river-discharge level in spring and increased concentration of phytoplankton.

Phytoplankton Community Abundance

Progressing downstream in the Delaware River from Trenton, there is a change in the composition and abundance of the phytoplankton. Concentrations of freshwater species decline from the tidal fresh region into the maximum turbidity zone in the region downstream of Marcus Hook. Here the cell abundance of all phytoplankton is markedly reduced. Further downstream, the concentrations of algae increases as the turbidity declines and estuarine species dominate the flora (Pennock 1985, Marshall 1992). However, these population concentrations are at a moderate state of development considering the high nutrient levels that exist annually in the estuary. The abundance and productivity of phytoplankton are prevented from reaching potentially greater levels by the relatively high suspended sediment load and the thorough mixing, both of which reduce the incident light available to the phytoplankton (Pennock 1985, Pennock and Sharp 1986).

Phytoplankton Species Composition

Throughout the world there are approximately 500 genera and 4,000 species of marine phytoplankton (Sournia, et. al.1991). Within the Delaware Estuary, there is a diverse flora of phytoplankton that is similar to other estuaries on the East Coast (Marshall and Alden 1993). In a one year study of the Delaware Estuary, Marshall (1992) reported 278 species and 119 genera within eight phylogenetic categories. Boyer (1916) recorded over 500 species in his study of freshwater and marine diatoms of the region. Species of phytoplankton in Delaware Bay were also studied by Waiting et al. (1979). These investigators identified 113 species with small flagellates (e.g., *Cryptomonas acuta*) predominating in summer, while diatoms were most abundant from fall through spring. The major diatom components of the spring bloom were *Skeletonema costatum* and *Thalassionema* spp. In the Delaware Estuary, Marshall (1992) noted the river stations had spring and summer maxima, with less development in fall and winter. Upstream, freshwater dominants included diatoms (*Skeletonema potamos*), cyanobacteria, and chlorophytes. Downstream, in saline waters, the diatoms *Skeletonema costatum* and *Asterionella glacialis* were the most abundant species, along with high concentrations of cryptomonads. These represent ubiquitous species that are common to other estuaries along the U.S. East Coast (Marshall 1984).

Phytoplankton represents the primary producer in most of the estuary's food web that support important finfish and shellfish fisheries. These fisheries have both a commercial and recreational value to the Delaware Estuary. They could be negatively impacted if this producer community were reduced in abundance, or if there was a marked population change in the flora. A change in the composition and abundance of the dominant phytoplankton components could alter the existing food chains.

Habitat Requirements

The basic requirements of phytoplankton include an adequate supply of nutrients (nitrogen, phosphorus, silicon, and others) and the availability of sufficient light for photosynthesis. In the Delaware Estuary, the levels of nutrients in the system are more than adequate, and the amount of available light has been sufficient to maintain a base population and a diverse assemblage of phytoplankton species throughout the year.

The high concentrations of nutrients that characterize the Delaware Estuary provide the potential for this system to support increased growth of phytoplankton. However, because the high suspended sediment load within the estuary has reduced the amount of light available to the phytoplankton; they have not fully utilized these nutrients.

Strategy Elements

This strategy includes eight major elements designed to establish nutrient criteria for the tidal rive and bay. The Delaware River Basin Commission will be the lead agency in this effort. These criteria will then be used in conducting assessments and in establishing effluent limitations, schedules and other NPDES permit requirements, as appropriate. The measures necessary to achieve water quality standards for nutrients in the estuary will depend on several factors including the degree of exceedence of the standards in each estuary zone, the degree of voluntary identification and reduction of nutrient sources, and attenuation through degradation processes and transport.

DRBC has identified eight (8) major activities to support the development of nutrient criteria for Zones 2-6 of the Delaware Estuary. It should be noted that these elements are being performed as resources allow and may occur concurrently, but not necessarily in chronological order.

These are presented below:

1) **EVALUATE EACH BASIN STATES NUTRIENT STRATEGIES FOR POTENTIAL USE BY DRBC,**

2) **MONITOR CONCENTRATIONS AND IMPACTS TO LIVING RESOURCES IN THE DELAWARE ESTUARY,**

3) **PREPARE OPTIONS FOR ESTABLISHING CRITERIA IN THE ESTUARY,**

4) **PREPARE CRITERIA FOR THE SELECTED OPTIONS,**

5) **PREPARE AN IMPLEMENTATION PLAN,**

6) **DEVELOP A EUTROPHICATION MODEL FOR ZONES 2-6 OF THE DELAWARE ESTUARY,**

7) **IDENTIFY AND QUANTIFY NUTRIENT SOURCES,**

8) **ADOPT REFINED NUTRIENT CRITERIA FOR ZONES 2 - 6 OF THE DELAWARE ESTUARY.**

A description of each of these elements follows.

1) EVALUATE EACH BASIN STATES NUTRIENT STRATEGIES FOR POTENTIAL USE BY DRBC

The approaches and tools developed by each of the basin states will be evaluated in developing nutrient options. Meetings will be held with the staff of the four basin states charged with developing nutrient criteria and standards to discuss their approaches and plans to adopt regulations.

The advisory committee structure has been effective in establishing communication with each basin state. Ongoing coordination with the Commission's Water Quality Advisory Committee will continue on at least a semiannual basis. The use of EPA's ecoregional approach will also be evaluated.

Tasks	Lead Agencies	Schedule
Set up meeting with the basin States to discuss strategies	DRBC,NYSDEC, NJDEP, PADEP, DNREC	2nd quarter 2008
Solicit State approaches	DRBC	Ongoing
Review EPA Ecoregional approach	DRBC	Ongoing

2) MONITOR CONCENTRATIONS AND IMPACTS TO LIVING RESOURCES IN THE DELAWARE ESTUARY.

The DRBC will work with partner organizations to monitor and assess estuary nutrient concentrations and associated chemical, physical and biological influences. DRBC expects these efforts to continue on an ongoing basis, evolving in response to the development of knowledge about the sources, dynamics, and effects of nutrients in the estuary.

A planned inventory will be essential to monitor the effectiveness of strategies to evaluate nutrient impact. The intent of this activity is primarily to document the occurrence of environmental effects from nutrient inputs to the basin. This would include fish kills, excessive algal blooms, depression of dissolved oxygen, or the presence of odors. The tasks in this element will continue and expand the existing data base on these occurrences in the basin. This data will also be essential to monitor the effectiveness of control strategies which are deemed to be implemented in reducing nutrient levels. It is anticipated that the strategy will identify/initiate effluent monitoring.

Tasks

Tasks	Lead Agencies	Schedule
1. Establish partnerships to identify responsibilities and frequency for monitoring nutrients in the system.	DRBC, Basin States, U.S. EPA, USGS	October 2009 to September 2015
2. Establish a web accessible inventory to allow for the public to report incidences of odor water discoloration, fish kills or other occurrence .	DRBC and States	CY 2008
3. Monitor water quality during the events identified in item 2.	DRBC, Basin States	July 2008 to June 2011
4. Determine impacts to living resources of the estuary seeking effects levels and thresholds	DRBC, State agencies, Academia	October 2008 to October 2015

3) PREPARE OPTIONS FOR ESTABLISHING CRITERIA IN THE ESTUARY

The DRBC staff will prepare several options for establishing nutrient criteria for the tidal Delaware River. The WQAC will be asked to establish a subcommittee to assist the staff in developing the options.

These optional approaches will be discussed with the Water Quality Advisory Committee. A consensus recommendation from the WQAC will ultimately be forwarded to the Commissioners.

Tasks	Lead Agencies	Schedule
Form WQAC subcommittee	DRBC	1st quarter 2008
Evaluate and rank options with a status report back to the WQAC	DRBC	3rd quarter 2008

4) PREPARE CRITERIA FOR THE SELECTED OPTION

Using the selected approaches, staff will develop draft narrative and/or numerical water quality criteria for Zones 2 - 6 of the estuary for the preferred options recommended by the WQAC.

These will be reviewed by the subcommittee and the WQAC.

Tasks	Lead Agencies	Schedule
Prepare draft Basis and Background document including narrative/numerical thresholds for Zones 2 - 6	DRBC	4th quarter 2008
Submit draft document for subcommittee review, comment, and revision	DRBC	1st quarter 2009
Submit draft document for WQAC review	DRBC	2nd quarter 2009

5) PREPARE AN IMPLEMENTATION PLAN,

Based on the outcomes of elements 3 and 4, DRBC will have a draft Basis and Background document. This will likely include numeric limits for TP, TN, Chlorophyll a, and water clarity for Zones 2 – 6 of the Estuary. DRBC staff will initiate the public participation process leading to the adoption of nutrient thresholds for the estuary.

Tasks	Lead Agencies	Schedule
Conduct public hearings.	DRBC staff	3rd quarter 2009
Prepare response to comment document.	DRBC staff	4th quarter 2009
Adoption of thresholds by the	DRBC staff	1st quarter 2010

Commission.		
Establish effluent limitations for NPDES discharges where necessary to ensure the water quality is met.	States	2010

6) DEVELOP AN EUTROPHICATION MODEL FOR ZONES 2-6 OF THE DELAWARE ESTUARY,

Mathematical models are an essential part of this strategy for several reasons. First, they allow the simulation of the important hydrodynamic forces that distribute substances within the estuary. In view of the complex hydrodynamic characteristics of the estuary including the significant tidal influence and regulated nature of the main tributaries to the estuary, a complex mathematical model is needed. Second, they permit the inclusion of significant fate processes for nutrients including sorption and uptake and use by plants. Third, they allow the sensitivity of the various transport and fate processes to be evaluated to both guide the collection of data during model calibration and validation, and the identification of significant sources of nutrients. Fourth, models can be used to identify the nutrient response threshold. Finally, they permit the evaluation of alternative source reduction strategies.

A calibrated and validated eutrophication model of the estuary for nutrient effects must be developed in order to identify nutrient effects in each of the five zones of the estuary, and to develop wasteload allocations for significant point sources and load allocations for significant non-point sources, if necessary. The model will include at least two major components: a hydrodynamic model and a water quality model. A three-dimensional hydrodynamic model of the estuary was recently developed as part of a program to evaluate changes to the salinity profile in the estuary as a result of channel deepening and sea level rise. This model may be the appropriate platform to build a eutrophication model for the estuary. A water quality model or models will need to be developed to simulate the loadings from the various source categories, and apply degradation processes. Other model components that will either be separate sub models or will be integrated into the water quality model include sediment and algal growth models. An expert panel will be formed to define the scope of the models and guide the modeling efforts. The DRBC will evaluate the need for nutrient criteria through an effect level approach which the DRBC will assess using models which evaluate those nutrient inputs to the system and the effects upon algal and other biological communities.

Modeling Tasks

Tasks	Lead Agencies	Schedule
1. Establish expert panel to guide model development and model calibration.	DRBC	Summer 2009

Tasks	Lead Agencies	Schedule
2. Evaluate existing models and define the scope of the modeling effort.	Expert panel, DRBC, States, U.S. EPA	Fall 2009
3. Develop mathematical model to simulate the transport and fate of nutrients in the Delaware Estuary.	DRBC	Jan 2010 to Sept 2010
4. Perform calibration and validation of the eutrophication model.	DRBC	Oct 2010 to Sept 2011

7. IDENTIFY AND QUANTIFY NUTRIENT SOURCES

Once initial criteria are set, the DRBC will evaluate the effectiveness using indicators developed by the DRBC advisory committees including the WQAC and Monitoring Advisory Committee to determine whether the new nutrient criteria are being met.

Identification of the significant sources of nutrients and appropriate control strategies to reduce or eliminate these sources is needed. Approaches to be used in this activity include proactive, voluntary efforts on the part of responsible parties to identify and reduce direct and indirect sources of nutrients, and regulatory efforts by government agencies responsible for the various source categories to control the release of nutrients to the estuary. If determined to be necessary, regulatory strategies to control nutrient sources to the estuary will be evaluated. In view of the numerous source categories of nutrients including nitrogen and phosphorus, these approaches may include the establishment of effluent limitations in NPDES permits where necessary, voluntary efforts by responsible parties to reduce or eliminate nutrient inputs to the estuary, and pilot studies of new and innovative techniques to control nutrients.

Using the initial collection results and the planned eutrophication model, sensitivity runs will be used to identify those source categories and specific sources for which additional monitoring is necessary. The DRBC is also evaluating the use of an effect level approach to develop the criteria. At present, algal stimulation studies are progressing. It is anticipated that this data will be useful to identify nutrient levels which may stimulate algal communities.

Tasks

Tasks	Lead Agencies	Schedule
1. Conduct source identification and control study in the Delaware Basin.	DNREC, NYSDEC, PADEP,NJDEP, DRBC	ongoing

Tasks	Lead Agencies	Schedule
2. Evaluate monitoring of wastewater, cooling water and storm water discharges from point sources.	DRBC, States and NPDES permittees	May 2008 to May 2009
3. Collect ambient, tributary and source data.	DRBC, U.S. Geological Survey	May 2008 to May 2009
4. Evaluation of Algal Stimulation data.	DRBC	2nd quarter 2009
5. Establish data base.	DRBC	October 2008, CY 2009

8) ADOPT REFINED NUTRIENT CRITERIA FOR ZONES 2-6 OF THE DELAWARE ESTUARY

DRBC anticipates that the performance of tasks in elements 5 and 6 will yield a conceptual linkage between nutrient loads, surface water concentrations, and effects. This linkage will provide the basis for development of refined nutrient criteria. This activity would also encourage the evaluation nitrogen/phosphorus concentration and development of a ratio based upon the scientific literature.

DRBC staff will initiate the public participation process leading to the adoption of the refined nutrient criteria for the estuary.

Tasks	Lead Agencies	Schedule
Prepare basis and background document, including numerical criteria	DRBC	1st quarter 2013
Submit for WQAC review	DRBC	2nd quarter 2013
Conduct public hearings	DRBC	3rd and 4th quarters 2013
Prepare response to comments document	DRBC	1st quarter 2014
Adoption of Criteria by the Commission	DRBC	2nd quarter 2014

NON-TIDAL DELAWARE RIVER NUTRIENT CRITERIA STRATEGY

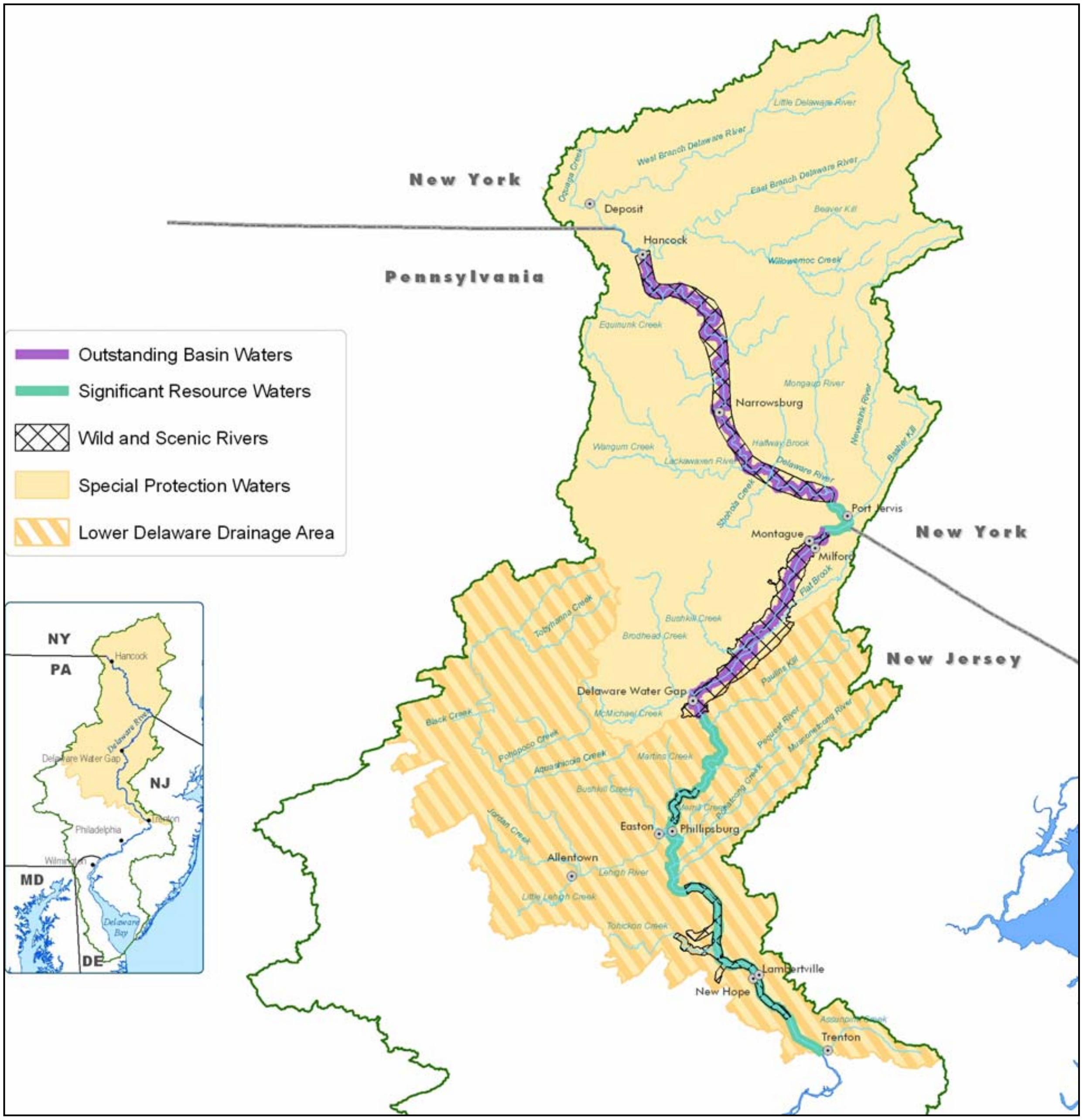
Background

The non-tidal Delaware River (Figure 2) may be characterized by its nutrient chemistry into three major reaches. The upper Delaware River from Hancock, NY to Port Jervis, NY, is generally nutrient-poor (TP<30 µg/l), cold, shallow, and fast-flowing through the Appalachian Plateau ecoregion. The middle Delaware River, from Port Jervis to Easton, PA, is slightly higher in nutrient concentrations (TP 30-80 µg/l), warmer, with more extensive pools and shorter riffles flowing through the Ridge and Valley physiographic region. The lower Delaware River, from the Delaware Water Gap to the Lehigh River confluence, resembles the middle Delaware but with slightly higher nutrient concentrations and distinct limestone influences. Below the Lehigh River and extending to Trenton, NJ, the lower Delaware River is relatively high in nutrient concentrations (TP>100 µg/l), warm, with very long pools, fewer riffles, and extensive urbanization effects. The lower Delaware flows through the Ridge and Valley and Piedmont ecoregions.

Of the three major primary producer groups that make direct use of available Delaware River nutrients, the periphyton community dominates at most times over phytoplankton and macrophytes in terms of biomass. Phytoplankton may be significant at times, particularly in large, warm, slow-flowing pools with sufficient retention time for development. Such pools are common between Point Pleasant, PA and Trenton, NJ. Macrophytes are uneven in distribution, but may also become very significant throughout the Delaware River in terms of biomass during extended periods of low flow. However, throughout the seasons, periphyton are always present in sufficient quantity to drive daily dissolved oxygen and pH water quality patterns. During periods of low flow, all three groups may contribute significantly to wide daily swings in dissolved oxygen and pH, and violations of water quality standards are increasingly likely during low flow periods.

In the non-tidal portion of the Delaware River, there are known reaches that have no nutrient problems, oligotrophic and probably phosphorus-limited reaches such as the upper and middle Delaware, and they are protected by antidegradation policy. Existing Water Quality (EWQ) may be more stringent than necessary to protect the designated uses. In the lower Delaware, however, where phosphorus and nitrogen are both in plentiful supply, there have been occasional nuisance algal blooms, violations of pH criteria, occasional fish kills, and extensive growth of an invasive exotic macrophyte (Myriophyllum spicatum) during prolonged low-flow periods. In this reach of the Delaware, antidegradation water quality targets will maintain existing water quality but may not be protective of aquatic life, recreation and drinking water uses.

Figure 2. Non-Tidal Portion of the Delaware River Basin Mainstem River.



It is imperative that more continuous monitoring be conducted in the upper and middle Delaware. It is not known if wide daily ranges of dissolved oxygen and pH occur in the Delaware River north of Point Pleasant, because there are no continuous monitors in operation along the upper 130 miles of river. At some stations in the Upper Delaware, instantaneous samples of maximum daily pH greater than 9.5 have been recorded in recent years. It may be possible that occasional eutrophication events occur even in areas of the Delaware River's best water quality. Continuous monitoring will be necessary for establishment of nutrient criteria representing thresholds of nitrogen and phosphorus that drive primary production toward dissolved oxygen and pH standard violations. Only in recent years has DRBC begun to study effects of nutrients upon aquatic life in the non-tidal Delaware River. It will be necessary to demonstrate effect levels of nutrients upon aquatic life in order to create nutrient criteria protective of the aquatic life use. If no thresholds are evident, or if it is found that nutrients have no effect upon aquatic life in the non-tidal river, the designation as Special Protection Waters and the implementation of the antidegradation policies will protect the river from nutrient pollution.

In 2005, DRBC conducted a pilot study for periphyton monitoring of the Delaware River. Limited results indicate a potentially strong relationship between nutrients and algal indicators. The most promising algal indicator is a ratio between abundance of high nutrient optima species vs. low nutrient optima species, developed by the Academy of Natural Sciences of Philadelphia (Potapova and Charles 2007) for the NJ Algal Indicators Project (Ponader et. al 2007). Another diatom metric commonly used among basin states is percent eutrophic diatoms, that also produces a strong signal to increased nutrient concentrations. There were only 5 sites included in the 2005 study, but expanded sampling of 25 sites along 200 miles of the Delaware River, begun in 2006, may reveal clearer patterns and possibly thresholds for each major Delaware River reach.

The 2005 periphyton pilot survey (Limbeck and Smith 2007), found that eutrophication due to high nutrient concentrations may be problematic in the lower non-tidal portion of the Delaware River. DRBC will conduct annual periphyton community monitoring in richest targeted habitat for the purpose of biocriteria development related to nutrients and eutrophication. After sufficient data has been collected, biological criteria for the non-tidal portion of the Delaware River will be proposed. DRBC is following recent guidance and publications relating nutrients, eutrophication, urbanization, sedimentation and rapid flow regime changes to algal community indicators (Hill et. al 2000; Kelly et. al 2001; Kentucky DEP 2002; Ponader and Charles 2003; Potapova et. al 2004; Ponader et. al 2007; Potapova and Charles 2007).

DRBC also collects benthic macroinvertebrates annually at 25 fixed sites along the Delaware River. Using 6 years of records (2001-2006), benthic metrics will be investigated for relationships with nutrient concentrations. Threshold levels of nutrients may be determined through correlation and regression analyses, as demonstrated by Blocksom and Paul (2007). DRBC will also employ a benthic macroinvertebrate nutrient index developed for New York State (Smith et. al 2007) to determine potential nutrient thresholds in support of criteria development.

In addition, DRBC performed algal biostimulation / nutrient addition tests on water samples from six sites in the Lower Delaware River in 2006 and 2007. Water column samples were used in a phytoplankton biostimulation test. This included a modified nutrient addition bioassay. The water samples were also analyzed for carbon and nutrient concentrations to compare and contrast ambient data to levels of nutrients that stimulate phytoplankton growth.

Working toward definition of nutrient limitations and nutrient thresholds for algal growth and community composition, another study is planned for 2008 that combines biological and chemical monitoring. Using Matlock periphytometers (Matlock et. al 1998), in-situ sampling of algae with various concentrations of nutrients will be evaluated to determine the algal growth effects of nutrient levels in the upper, middle and lower Delaware River.

Non-Tidal Delaware River Nutrient Strategy

The following strategy applies to the Non-Tidal Delaware River, approximately 200 miles of interstate waters from Hancock, NY to Trenton, NJ. Most of this portion of the river has Wild and Scenic Rivers Act status, and has been declared by DRBC as Special Protection Waters, where antidegradation protection of water quality is the primary management tool.

Given the context of the activities mentioned above, the DRBC strategy for development of nutrient criteria is based upon a number of policies and multiple lines of evidence.

Guiding Principles and Policies

1. Apply the Special Protection Waters rules to maintain Existing Water Quality (EWQ) at river and tributary control points located between Hancock, New York and Trenton, New Jersey.

2. Nutrient criteria will be developed to protect the following uses: aquatic life; water supply; recreation; aesthetics; and preservation of the Wild and Scenic status of the Delaware River.

3. In order to protect designated uses, "cultural enrichment" or unnatural eutrophication must be prevented. Cultural enrichment is defined as "human activities that results in increased nutrient loads to a water body." Eutrophication is defined as "the increase of nutrients in water bodies either naturally or artificially by pollution." Eutrophic is defined as "abundant in nutrients and having high rates of productivity frequently resulting in oxygen depletion below the surface layer." (U.S. EPA 2000)

4. Where data gaps exist for nutrient criteria development, DRBC is committed to obtaining the necessary information. Existing data should be used whenever possible. An extensive nutrient data set exists where the DRBC Lower Delaware Monitoring Program has defined EWQ at Lower Delaware River control points; where the Delaware River Biomonitoring Program has collected macroinvertebrate and periphyton samples; and where state and federal agencies have established long term monitoring records. The DRBC/NPS Scenic Rivers Monitoring Program has adopted the control point approach to water quality monitoring, and is proceeding to fill data gaps in the upper 110 miles of river.

5. DRBC has begun, and will continue, to evaluate impacts of increased nutrient concentrations upon aquatic life in the Delaware River.

6. Criteria may include narrative and numeric limits for total phosphorus, total nitrogen, water clarity, oxygen and pH daily ranges, disinfection byproducts, algal toxins, aesthetics and recreational use indicators, chlorophyll concentrations and biomass measures, and biocriteria consisting of selected algal and macroinvertebrate metrics.

7. DRBC must determine if EWQ, as defined in the Special Protection Waters rules, is protective of nutrient impacts on aquatic life, drinking water, and recreation uses.
8. The Water Quality Advisory Committee and the Monitoring Advisory Committee will oversee the nutrient criteria development process, and additional experts will be enlisted to provide guidance and peer review.

Nutrient Strategy Elements

1. Finalize Existing Water Quality Rules for the Lower Non-Tidal Delaware River.
2. Adopt Control Point Based EWQ for the Middle and Upper Delaware River.
3. Conduct Investigations to Determine Nutrient Effects Upon Designated Uses.
4. Evaluate Basin State Nutrient Criteria Strategies.
5. Review Options and Approaches for Establishing Criteria.
6. Select Approaches and Prepare Draft Nutrient Criteria.
7. Adopt Nutrient Criteria, as Appropriate
8. Identify and Quantify Nutrient Sources to the Delaware River.
9. Develop Eutrophication Models for Each River Zone.
10. Monitor Long Term for Criteria Effectiveness.

Discussion of Elements

<u>1. Finalize Existing Water Quality Rules for the Lower Non-Tidal Delaware River.</u>

Implementation: 2007-2008

As of November 2007, Special Protection Waters rules have been published for permanent designation of the Lower Delaware (77 miles of river) as Significant Resource Waters. Part of this rule contains definition of EWQ at 24 control points on the Delaware River and selected tributaries. Table 1 shows nutrient EWQ targets at these locations.

Table 1. Nutrient EWQ at Delaware River Interstate Control Points.

River Mile, Site	TP median mg/l	TP lower 95% CL mg/l	TP upper 95% CL mg/l	TN median mg/l	TN lower 95% CL mg/l	TN upper 95% CL mg/l
330-250 Upper Delaware Reachwide	0.029	0.027	0.031	0.495	0.428	0.573
250-208 Middle Delaware Reachwide	0.027	0.025	0.029	0.412	0.380	0.448
207.50 Portland	0.04	0.03	0.05	0.86	0.74	1.05
197.84 Belvidere	0.04	0.03	0.05	0.89	0.82	1.11
183.82 Easton	0.05	0.04	0.06	1.19	1.01	1.35
174.80 Riegelsville	0.08	0.06	0.12	1.44	1.31	1.62
167.70 Milford	0.09	0.07	0.11	1.47	1.23	1.68
155.40 Bulls Island	0.10	0.07	0.11	1.42	1.20	1.53

148.70 Lambertville	0.10	0.08	0.12	1.42	1.27	1.83
141.80 Washington Crossing	0.10	0.07	0.12	1.36	1.23	1.67
134.34 Trenton	0.10	0.07	0.12	1.41	1.20	1.69

These nutrient definitions represent EWQ at the time of designation, and DRBC project review activities center on protecting water quality at these levels. While these criteria represent EWQ, they are not linked to uses and effect levels remain unknown. Thus, this first step toward nutrient criteria intends to fix existing nutrient conditions at least until aquatic life, drinking water, and recreation effect levels can be determined.

2. Adopt Control Point Based EWQ for the Middle and Upper Delaware River.

Implementation: 2011-2012

It may be noted in Table 1 that EWQ is represented as reach-wide concentrations, which have proven difficult to implement in project review and assessment. It is the intention of DRBC to revise the Upper and Middle Delaware reach wide EWQ criteria by converting to the site-specific control point approach. While making use of historical water quality data whenever possible, it has been necessary to collect additional water quality data (particularly nutrient data) to accomplish the conversion to control points. In 2006 the DRBC, National Park Service, and U.S. Geological Survey undertook data collection at 18 Delaware River locations and 37 tributary locations in the Upper and Middle Delaware. This effort will continue until sufficient data have been gathered to establish EWQ at all 55 locations. Completion is anticipated from 2009 to 2011, depending on location.

3. Conduct Investigations to Determine Nutrient Effects Upon Designated Uses.

Aquatic Life

Completion: 2008-2013

DRBC will make use of annual macroinvertebrate and periphyton surveys and special studies to complete this task. As noted earlier, DRBC has undertaken a phytoplankton nutrient stimulation study in 2006 and 2007 to determine limiting nutrients in the Lower Delaware. A number of data analyses and special studies must be conducted in order to identify nutrient thresholds for aquatic life:

1. Macroinvertebrate Survey: 2001-2006 data will be analyzed in several ways, including regression and correlation analyses, and application of the Nutrient Biotic Index (NBI, Smith et. al 2007) to discover potential effect levels of nutrients upon the macroinvertebrate community.

2. Periphyton Survey: Given the fairly strong nutrient gradient in the Delaware River, there appears to be a strong response in diatom community composition and abundance. DRBC is working with the Academy of Natural Sciences of Philadelphia to uncover patterns of response to increased nutrients. 2006 and 2007 results are pending, and will guide future actions if necessary.

3. Special Studies: Funding must be sought to complete in-situ studies of periphyton response to nutrient addition. DRBC is seeking funding to conduct a Matlock periphytometer study in the Upper, Middle and Lower Delaware River in 2008 (Matlock et. al 1998). This relatively inexpensive instream experiment would help to determine nutrient limitations to periphyton, as well as algal community changes associated with nutrient addition in each major river zone. However, results may not reveal aquatic life thresholds, and additional research will be required.

Other future efforts should be guided by an expert panel.

Drinking Water and Recreation

Completion date: unknown

No plans have yet been made to determine nutrient thresholds protective of these uses. Guidance should be provided by an expert panel, and DRBC will plan investigations accordingly. New York State DEC has successfully used criteria for disinfection by-products, algal toxins, and frequency of taste and odor problems for protection of water supplies from eutrophication (Calliman 2007). For recreation use protection, New York has conducted user surveys and related results to total phosphorus, secchi depth, and algal toxins in lakes. While it is unclear how such a user survey might be conducted in relation to the Delaware River, it may be possible to link recreation experience with the degree of eutrophication in the Delaware. Guidance and funding are needed to conduct these investigations.

<u>4. Evaluate Basin State Nutrient Criteria Strategies.</u>

Completion date: 2008

As an interstate compact agency, DRBC must strive for consistency with its member states in its approach to nutrient criteria development. To ensure this, a DRBC staff review of basin state nutrient strategies will occur in 2008. Results may guide and influence nutrient criteria approaches and decision making, and should provide an additional line of evidence in choice of final criteria. No matter which approach is selected, each of the Basin states needs to agree to the final approach.

<u>5. Review Options and Approaches for Establishing Criteria.</u>

Completion date: unknown, probably before 2010

DRBC is open to all options and approaches to nutrient criteria development. The distribution or percentile approach is being employed in the EWQ definition; the NBI makes use of the reference approach; and in-situ periphyton studies and algal stimulation studies employ the effect level approach. Water quality modeling may reveal distinct patterns and thresholds for dissolved oxygen and pH responses. Results from any of these are comparable with EPA's ecoregional approach. As results become available, each approach should reveal another line of evidence toward choice of final criteria. Strengths and weaknesses of each approach will be evaluated, and those approaches most scientifically defensible will be accorded the most weight in final determination of criteria.

6. Select Approaches and Prepare Draft Nutrient Criteria.

Completion date: unknown, probably before 2012

The selection of the "best" approach to nutrient criteria may not be entirely necessary as long as a weight of evidence approach is considered. However, cost considerations and expedience may require hard choices about which approach to use. In the drafting phase of criteria development, the approach that gives the most information and is most scientifically defensible (by peer review) may be the only approach necessary under strict budget constraints. Participation of an expert panel and guidance of DRBC advisory committees is critical in this step.

7. Adopt Nutrient Criteria, as Appropriate

Completion date: 2012-2014

8. Identify and Quantify Nutrient Sources to the Delaware River.

Completion date: 2005-2011

The control point approach to water quality monitoring makes it relatively easy to identify which tributaries contribute the greatest loadings of nutrients to the Delaware River. This has already been accomplished in the Lower Delaware (Limbeck 2005). DRBC monitoring programs gather data on flow and concentrations from major tributaries, and this enables identification of major loadings. Within tributary watersheds, however, we must rely on land use and state agency information to determine the largest nutrient sources. Also, the size of the Delaware River watershed makes this task extremely complex.

9. Develop Eutrophication Models for Each River Zone.

Completion date: 2011-2014

Eutrophication models in each major river zone (upper, middle and lower Delaware River) will provide the framework for integration of sources, quantities, and effects. If strong stressor-response relationships are discovered, then predictive modeling will enable implementation of criteria. Some models already are under construction at DRBC, and additional data needs to be collected in order to construct, calibrate, and validate the models.

10. Monitor Long Term for Criteria Effectiveness.

Completion date: Ongoing

The DRBC/NPS Scenic Rivers Monitoring Program, DRBC Lower Delaware Monitoring Program, and Delaware River Biomonitoring Program are committed to long term physical, chemical and biological monitoring of the Delaware River. As the nutrient criteria development process evolves, the monitoring programs will be adjusted to include parameters and indicators for tracking effectiveness of the criteria.

Critical Needs for Nutrient Criteria

At present, DRBC can go forward with EWQ-based criteria, but for true effect-level criteria we need support for the following:

1. Funding for seasonal upper river continuous monitors for water quality – the northern-most water quality monitor is at Point Pleasant. About 170 miles of river are not covered by continuous monitoring. The continuous monitors should measure dissolved oxygen, pH, temperature, specific conductance, and turbidity. Water Quality Zones 1A, 1B, 1C, 1D, much of 1E, and Zone 2 have no continuous monitors. It is recommended that USGS real-time water quality monitors be placed seasonally at the following existing flow gages: Lordville, Callicoon, Barryville, Millrift (no gage at present), Montague, Stroudsburg, Belvidere, Sandts Eddy (no gage at present), Riegelsville, and Burlington.

2. Funding and technical assistance is needed for in-situ periphyton effect level studies of the non-tidal Delaware River, and derivation of nutrient thresholds. DRBC has scheduled a Matlock periphytometer study for summer 2008, but the study remains unfunded. In addition, DRBC has an opportunity to cooperate with the National Park Service and U.S. Geological Survey to conduct low-level hyperspectral imagery overflights of the Delaware River at low-flow conditions, in order to identify nuisance vegetation, map aquatic plant beds and habitats, and pollution source identification. This activity is in the proposal phase for NPS funding, but success of the project may hinge on leverage of NPS funds.

3. Support for formation of an expert panel, for facilitation of regulated community participation with the rulemaking process, and for peer-review of all scientific studies and findings.

4. Assistance with problem definition and linkage of information. We do not know what quantitatively constitutes eutrophic conditions in the Delaware River. We do not know whether EWQ is protective of uses, particularly in the lower non-tidal river and estuary.

5 Continued funding and technical assistance with studies employing the reference approach. The Delaware River Biomonitoring Program intends to employ more randomized, multi-habitat biomonitoring of macroinvertebrates and diatoms. DRBC biomonitoring presently samples only richest targeted habitat, riffles and runs, with N of 25/year. Greater responses to nutrient stressors may be associated with biota of pools, glides and back-channels which are all under-sampled. Such investigations, which may reveal nutrient thresholds, are currently unfunded and staff-time limited.

Table 2. Summary of Non-Tidal Nutrient Criteria Strategic Elements and Milestones.

Note that these elements are not sequential, and many tasks are being completed concurrently.

Strategy Element	Task and Anticipated Completion Date
1. Finalize Existing Water Quality Rules for Lower Delaware Special Protection Waters	Adopt by Spring 2008
2. Upper and Middle Delaware Control Point Based EWQ	Complete EWQ definition by 2010
	Rule Proposal 2011
	Adopt in SPW Rules 2012
3. Determine Nutrient Effects Upon Designated Uses	Aquatic Life: Existing Macroinvertebrate Data Analyses 2008
	Aquatic Life: Analyses of 2006 and 2007 periphyton surveys 2008
	Aquatic Life: In-Situ Nutrient Bioassay Study of Periphyton 2008 or 2009
	Aquatic Life: Other Investigations to be determined
	Drinking Water and Recreation: To Be Determined
4. Evaluate Basin State Nutrient Criteria Development Strategies	Evaluation and Coordination 2008
5. Review Options and Approaches for Establishing Nutrient Criteria	Agreement of States and DRBC by 2010
6. Select Approaches and Prepare Draft Criteria	Review Existing Information with Nutrient Workgroup, Select Best Approach 2010
	Prepare Draft Criteria 2011
	Expert Panel Peer Review 2012
7. Adopt Nutrient Criteria, As Appropriate	Commission Actions 2012-2014
8. Identify and Quantify Nutrient Sources	Ongoing 2005-2014
9. Develop Eutrophication Models for Each River Zone	Lower Delaware 2011
	Upper Delaware 2012
	Middle Delaware 2012
10. Monitor Long Term for Criteria Effectiveness	Ongoing

References

Blocksom, K. and M. Paul. 2007. N-STEPS Webcast: Statistical Tools for Making Sense of Data. July 11, 2007 webcast at http://n-steps.tetratech-ffx.com/

Callinan, C. 2007. Update on Nutrient Criteria Development Process for Ponded Waters in New York State. NYSDEC, Division of Water, Albany, NY. October 2, 2007 presentation by Scott Kishbaugh during EPA Region 2/3 Regional Technical Advisory Group Nutrient Workshop, Philadelphia, PA.

DRBC 2006. Delaware River Biomonitoring Program: Quality Assurance Project Plan.

Hill, B. H. et. al 2000 Use of periphyton assemblage data as an index of biotic integrity. J. N. Am. Benthol. Soc. 19(1): 50-67

Kelly, M. G. et. al 2001. The Trophic Diatom Index: A Users Manual. Revised Edition. R&D Technical Report E2/TR2, Environment Agency, Bristol, UK.

Kentucky DEP 2002. Methods for assessing biological; integrity of surface waters. Kentucky DEP, Div. of Water, Ecological Support Section, Frankfort, KY.

Limbeck, R.L. 2005. Nutrients in the Lower Non-Tidal Delaware River, 2001-2004: Monitoring Results and Management Applciations. SETAC Annual Conference, Baltimore, MD, November 2005.

Limbeck, R.L. and G.D. Smith. 2007. Pilot Study: Implementation of a Periphyton Monitoring Network for the Non-Tidal Delaware River. Delaware River Basin Commission, West Trenton, NJ. March 2007.

Marshall, H. 1984. Phytoplankton distribution along the eastern coast of the USA. Part V. Seasonal density and cell volume patterns for the northeastern continental shelf. J. Plankton Res. 6: 169-193

Marshall, H. And R. Alden. 1993. A comparison of phytoplankton assemblages in the Chesapeake and Delaware estuaries, with emphasis on diatoms. Hydrobiologia 269/270:251-261

Matlock, M.D., M.E. Matlock, D.E. Storm, M.D. Smolen, and W.J. Henley. 1998. Limiting nutrient determination in lotic ecosystems using a quantitative nutrient enrichment periphytometer. J. AWRA 34(5): 1141-1147

Pennock, J. 1985. Chlorophyll distributions in the Delaware estuary: regulation by light-limitation. Estuar. Coast. Shelf-Sci. 21:711-725

Pennock, J., and J. Sharp. 1986. Phytoplankton production in the Delaware Estuary: temporal and spatial variability. Mar. Ecol. Prog. Ser. 34:143-155

Ponader, K. C. and Charles 2003. Understanding the Relationship Between Natural Conditions and Loadings on Eutrophication: Algae Indicators of Eutrophication for New Jersey Streams. Final Report No. 03-04, Year 2. NJDEP Of Sci. Res. & Tech. And the Patrick Center for Environmental Research.`

Ponader, K. C. et. al 2007. Diatom-based TP and TN inference models and indices for monitoring nutrient enrichment of New Jersey streams. Ecological Indicators 7(1): 79-93.

Potapova, M. et. al 2004. Quantifying species indicator values for trophic diatom indices: a comparison of approaches. Hydrobiologica 517:25-4.1

Potapova M. and D. F. Charles 2007. Diatom metrics for monitoring eutrophication in rivers of the United States. Ecological Indicators 7(1): 48-70.

Santoro, E. D. and J. Sharp. 1999. Long Term Improvement in Water Quality in the Delaware Estuary. American Society of Limnology and Oceanography Conference, Santa Fe, NM, February 1999.

Santoro, E. D., Delaware Estuary Monitoring Report Covering Monitoring Developments and Data Collected or Reported in 2003. Delaware Estuary Program Report July 2004

Santoro, E. D. 2000., Delaware Estuary Monitoring Report Covering Monitoring Developments and Data Collected or Reported in 1998. Delaware Estuary Program Report July 2000

Sharp, J. 1988. Trends in nutrient concentrations in the Delaware estuary. Pages 77-92 in S. Majumdar, E. Miller, and L. Sage, eds. Ecology and restoration of the Delaware River Basin. Penn. Acad. Of Science, Philadelphia.

Sharp, J., L. Cifuentes, R. Coffin, J. Pennock, and K. Wong. 1986. The influence of river variability on the circulation, chemistry, and microbiology of the Delaware estuary. Estuaries 9:261-269.

Sharp, J., 1994 What not to do about nutrients in the Delaware Estuary. Pages 423-428 in K. R.,Dyer R. J. Worth, eds. Changes to fluxes in Estuaries. Published by Olsen & Olsen Fedensborg Denmark pgs 423-428

Smith, A.J., R.W. Bode, G.S. Kleppel. 2007. A nutrient biotic index (NBI) for use with benthic macroinvertebrate communities. Ecological Indicators 7(2): 371-386.

Sournia, A. M. et. al.1991 Marine phytoplankton: how many species in the world ocean? J. Plankton Res. 13:1093-1099

U.S. EPA. 1998a. Water Quality Criteria and Standards Plan – Priorities for the Future. U.S. EPA, Office of Water, Washington, D.C. June 1998. EPA-822-R-98-003

U.S. EPA. 1998b. National Strategy for the Development of Regional Nutrient Criteria. U.S. EPA, Office of Water, Washington, D.C. June 1998. EPA-822-R-98-002.

U.S. EPA. 2000a. Ambient Water Quality Criteria Recommendations: Information Supporting the Development of State and Tribal Nutrient Criteria for Rivers and Streams in Nutrient Ecoregion VII. U.S. EPA, Office of Water, Office of Science and Technology, Health and Ecological Criteria Division, Washington, D.C. December 2000. EPA-822-B-00-018.

U.S. EPA. 2000b. Ambient Water Quality Criteria Recommendations: Information Supporting the Development of State and Tribal Nutrient Criteria for Rivers and Streams in Nutrient Ecoregion IX. U.S. EPA, Office of Water, Office of Science and Technology, Health and Ecological Criteria Division, Washington, D.C. December 2000. EPA-822-B-00-019.

U.S. EPA. 2000c. Ambient Water Quality Criteria Recommendations: Information Supporting the Development of State and Tribal Nutrient Criteria for Rivers and Streams in Nutrient Ecoregion XI. U.S. EPA, Office of Water, Office of Science and Technology, Health and Ecological Criteria Division, Washington, D.C. December 2000. EPA-822-B-00-020.

U.S. EPA. 2000d. Ambient Water Quality Criteria Recommendations: Information Supporting the Development of State and Tribal Nutrient Criteria for Rivers and Streams in Nutrient Ecoregion XIV. U.S. EPA, Office of Water, Office of Science and Technology, Health and Ecological Criteria Division, Washington, D.C. December 2000. EPA-822-B-00-022.

U.S. EPA. 2000e. Nutrient Criteria Technical Guidance Manual: Rivers and Streams. U.S. EPA, Office of Water, Office of Science and Technology, Washington, D.C. July 2000. EPA-822-B-00-002.

U.S. EPA. 2001a. Ambient Water Quality Criteria Recommendations: Information Supporting the Development of State and Tribal Nutrient Criteria for Rivers and Streams in Nutrient Ecoregion VIII. U.S. EPA, Office of Water, Office of Science and Technology, Health and Ecological Criteria Division, Washington, D.C. December 2001. EPA-822-B-01-015.

U.S. EPA. 2001b. Nutrient Criteria Technical Guidance Manual: Estuaries and Coastal Marine Waters. U.S. EPA, Office of Water, Office of Science and Technology, Washington, D.C. October 2001. EPA-822-B-01-003.