THE COST OF CLEAN WATER IN THE DELAWARE RIVER BASIN[1]

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ABSTRACT: The Delaware River has made a marked recovery in the half-century since John F. Kennedy's 1961 Delaware River Basin Commission (DRBC) Compact, Richard Nixon's 1970 EPA, and the 1970s Federal Clean Water Act Amendments. A first of its kind 1960s Delaware River benefit-cost analysis found it cost-effective to fund a multi-million-dollar waste load abatement program to raise dissolved oxygen levels to boatable and fishable standards to generate economic activity. Scientists have called for raising the 1960s DO standard along the Delaware River from 3.5 mg/l to at least 5 mg/l to protect anadromous American shad and Atlantic sturgeon and address the prospect of rising temperatures, sea levels, and salinity in the estuary. A 21st century marginal abatement cost (MAC) curve analysis shows it to be cost-effective to prioritize agricultural conservation and wastewater treatment investments in the Delaware River watershed to reduce 90% of the pollutant load (30 million lb/yr of nitrogen) for $160 million at 35% of the estimated $449 million annual cost. The estimated annual cost to reduce nitrogen loads and increase dissolved oxygen to meet a more stringent standard in the Delaware River includes $45 million for atmospheric NOX reduction, $130 million for wastewater treatment, $132 million for agriculture conservation, and $141 million for urban stormwater retrofitting.

(KEY TERMS: watershed; water quality; economics)

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INTRODUCTION

Nutrient pollution due to high loads of nitrogen and phosphorus hinders the clean water economy due to costly impacts on tourism, commercial fishing, recreation, hunting, real estate, and water treatment (Gilbert et al. 2010). In waterways with nutrient pollution, the tourism industry loses near $1 billion annually through reduced fishing and boating activity. Waterfront property values decline near unsightly and odorous algal blooms. Annual commercial fishing losses due to nutrient pollution and low dissolved oxygen levels exceed tens of millions of dollars. Algal blooms in drinking water supplies increase the costs of treatment needed to remove taste and odor problems and disinfection by-products. Noting that 50 % of the nation's streams have medium to high levels of nitrogen and phosphorus and 78% of coastal waters experience eutrophication, the Environmental Protection Agency (EPA) has urged states to adopt numeric nutrient criteria to reduce nitrogen and phosphorus loads to U.S. waters (Stoner 2011).

Nutrient load reduction costs are high and range from $35 million in the Wisconsin Fox-Wolf River watershed (Schleich et al. 1996) to $203 million in the Connecticut River/Long Island Sound Basin (Evans 2008). The Chesapeake Bay Program (2004) estimated a $1.0 billion cost to clean up the Chesapeake Bay watershed. Rabotyagov et al. (2010) concluded $1.8 billion would be needed to reduce nutrient loads and increase dissolved oxygen levels in the Upper

Mississippi River Basin. Lyon and Farrow (1995) reported to EPA that stormwater programs designed to comply with the Federal Clean Water Act would cost up to $14 billion per year.

The Interstate Commission on the Delaware River Basin (1940) once called the Delaware River near Philadelphia "one of the most grossly polluted areas in the United States". In 1961, President John F. Kennedy and the governors of Delaware, New Jersey, New York, and Pennsylvania signed the Delaware River Basin Commission (DRBC) Compact as one of the first models of Federalism or shared power in water management between the Federal government and the states (Mandarano et al. 2008). For fifty years, the DRBC (1961) has been empowered by this compulsory Federal-state compact to conduct water pollution control programs on the Delaware River (Albert 1988). The Delaware has a long history of nutrient pollution (Sharp and Church 1981, Sharp et al. 1982, Sharp et al. 1984, Scudlark and Church 1993, Sharp 2006, and Church et al. 2006) but the estuary has recovered considerably in the last few decades due to restoration efforts by DRBC, EPA, and the states (Bricker et al 2007, Bain et al. 2010, and Sharp et al. 2009). A century-long DO record reconstructed by Sharp (2010) indicates the tidal Delaware has made one of the most extensive recoveries of any estuary in the world (Figure 1).

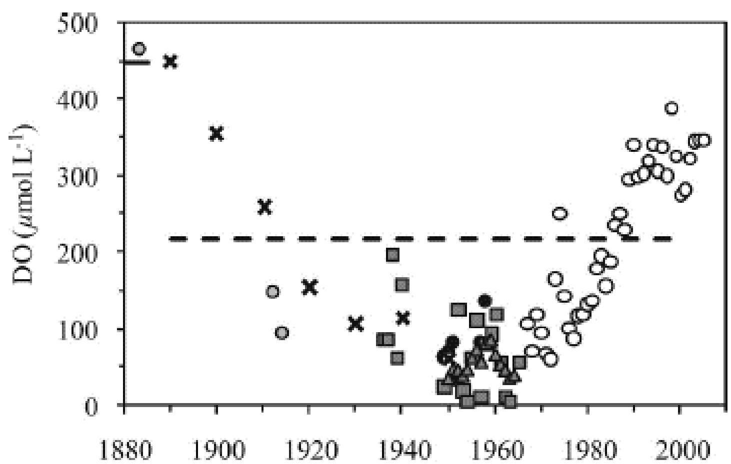

FIGURE 1. Dissolved Oxygen in the Delaware River near Philadelphia, 1880-present

(Sharp 2010)

While water quality has measurably improved in the Delaware Estuary since JFK signed the 1961 DRBC Compact, dissolved oxygen levels still do not fully meet the criteria of 3.5 mg/l during summer when water temperatures rise near 30°C (86°C) and DO saturation plunges to 50%. The DRBC has discussed setting more protective DO criteria along the tidal Delaware River (to 5 or 6 mg/l perhaps) to sustain year-round propagation of anadromous fish (Schneider 2007 and Silldorf and Fikslin, 2010). More stringent DO criteria would also address the prospect of atmospheric warming and rising sea levels that are projected to increase water temperatures, raise salinity, and further depress DO saturation.

RESEARCH OBJECTIVES

While recovery has been extensive, little is known about modern costs to restore the Delaware River to meet water quality standards. The objectives of this research are to estimate the marginal costs of strategies to restore the Delaware River to more protective year-round fishable water quality criteria in accordance with DRBC, Federal Clean Water Act, and State standards.

THE DELAWARE RIVER

While just the 33rd largest river in the U.S., the Delaware River is the longest undammed river east of the Mississippi, extending 390 mi (628 km) from the 3,000 ft (970 m) high Catskill Mountains in New York to the mouth of the Delaware Bay at Cape May, New Jersey (Figure 2). The river is fed by 216 streams including its two largest tributaries - the Schuylkill and Lehigh River - and drains 13,539 mi^2 (35,077 km^2) in Delaware, Pennsylvania, New Jersey, New York, and a small sliver of Maryland. The Delaware Basin covers just 0.4% of the continental U.S. yet supplies drinking water to 5% of the population and the first (New York City) and seventh largest (Philadelphia) metropolitan economies in the nation (Kauffman et al. 2010). Over 16 million people rely on the Delaware Basin for drinking water including 8.2 million people who live in the watershed and 8 million people who live outside the basin in New York City and central New Jersey (Table 1). Half of New York City's drinking water flows through an aqueduct from three reservoirs in the Catskill headwaters of the Delaware River. Between 2000 and 2010, the basin population increased by a half million people, a population equal to the cities of Camden, Easton, Trenton, and Wilmington (Figure 3). The Delaware River Basin supports over $25 billion in annual economic activity, $21 billion in ecosystem goods and services, is directly/indirectly responsible for over 500,000 jobs in Delaware, New Jersey, New York, and Pennsylvania (Kauffman 2016).

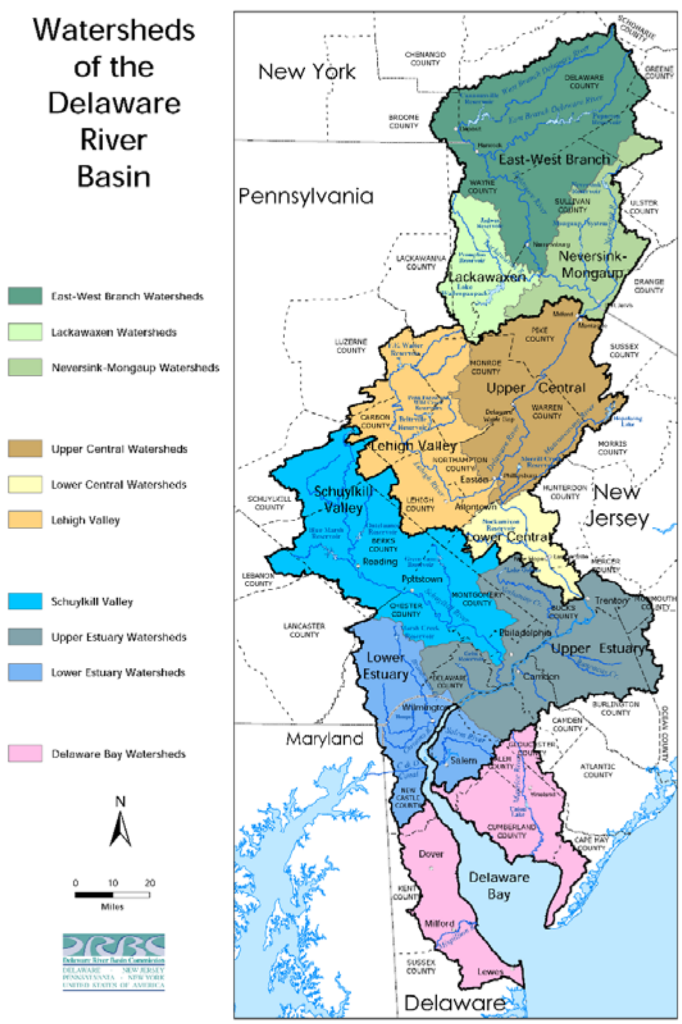

FIGURE 2. The Delaware River Basin (DRBC 2010)

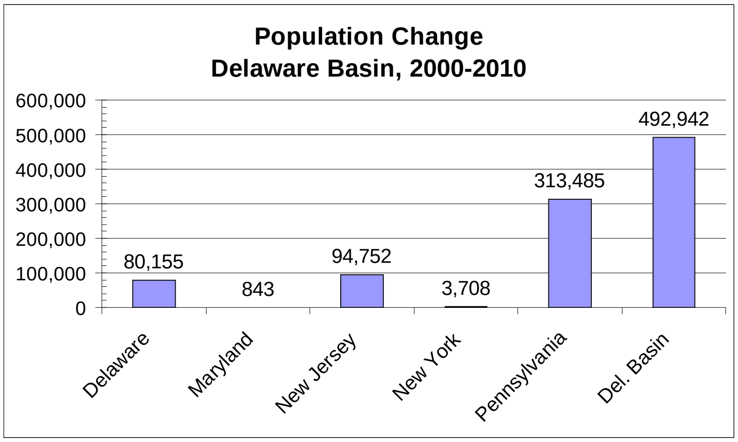

FIGURE 3**.** Population Change in the Delaware Basin, 2000-2010 (U.S. Census Bureau)

TABLE 1. Land Area, Population, and Employment in the Delaware Basin

State	Area (km^2)	Population[1] 2010	Economic Activity ($B)	Ecosystem Services ($B)	Jobs
Delaware	2,501	703,963		$2.5	34,500
New Jersey	7,675	1,945,966		$6.6	137,168
New York	6,623	121,160		3.5	70,776
Pennsylvania	16,278	5,478,577		8.6	286,801
Total	**33,077**	**8,250,000**	**25.3**	**$21.2**	**528,366**

1. U.S. Census Bureau 2010. 2. U.S. Bureau of Labor Statistics

WATER QUALITY CONSIDERATIONS

The Delaware Estuary extends 130 mi (208 km) from the Atlantic Ocean to the head of tide at Trenton (Sharp 2006). High nutrient loads discharged from urban tributaries near Philadelphia and rural streams along the bay are diluted by large volumes of saltwater as the bay widens toward the mouth of the bay (Sharp et al. 1986). Recirculation in the Delaware Estuary occurs every 8 days (Table 2) with half mixing with freshwater from the Delaware River at Trenton and Schuylkill, Lehigh, Brandywine and smaller tributaries and the other half from the Atlantic Ocean through the bay mouth (Bricker et al. 2007). The estuary is relatively turbid with a light extinction coefficient of 0.3-7.0 (Roman et al. 2000).

The DRBC (2008, 2010) classifies the Delaware River and Bay according to 10 non-tidal and tidal water quality management zones based on: (1) Agricultural, Industrial, and Public Water Supply, (2) Wildlife, Fish and Aquatic Life, (3) Recreation (Primary Contact Swimming/Secondary Contact Boating, Fishing, Wading, (4) Navigation, and (5) Waste Assimilation designated uses (Figure 4). In the tidal Delaware, 24-hour DO criteria varies from 5 mg/l between Trenton and Rancocas Creek (RM 108), 3.5 mg/l from Rancocas Creek to Delaware Memorial Bridge, 4.5 mg/l from Delaware Memorial Bridge to Liston Point below the C&D Canal, and 6 mg/l from Liston Point to the Atlantic Ocean. The minimum DO criteria is 6.5 mg/l during spring/fall from Trenton to Liston Point to allow for seasonal propagation of resident and anadromous fish.

TABLE 2. Characteristics of the Delaware River ((Roman et al. 2000 and Bricker et al. 2007)

Characteristic	**Value**
Drainage Area (km^2)	35,252
Population (2010)	8,200,000
Total Length (km)	628
Tidal Length (km)	155
Watershed/Estuary Ratio	18
Estuary Recirculation (days)	8
Light Extinction Coefficient	0.3-7.0

Despite high nutrient loading, the Delaware Estuary does not exhibit classic eutrophication symptoms of hypoxia or algal blooms as observed in Chesapeake Bay. Algal blooms are inhibited by the assimilative capacity of wetlands that rim the bay and low light levels in the well-flushed Delaware Estuary. The Delaware Estuary is one of the more turbid estuaries in the U.S. due to resuspension of clay bottom sediments by tidal currents that block 9/10 of the light, thus limiting photosynthesis and eutrophication from high nutrient loads. Since the 17-mile (27-kilometer) mouth of the Delaware Bay is wide compared to other estuaries, the Atlantic Ocean contributes significant tidal flushing and reoxygenation, thus limiting algal blooms that cause fish kills except during an occasional spring bloom in the mid estuary (Bricker et al. 2007).

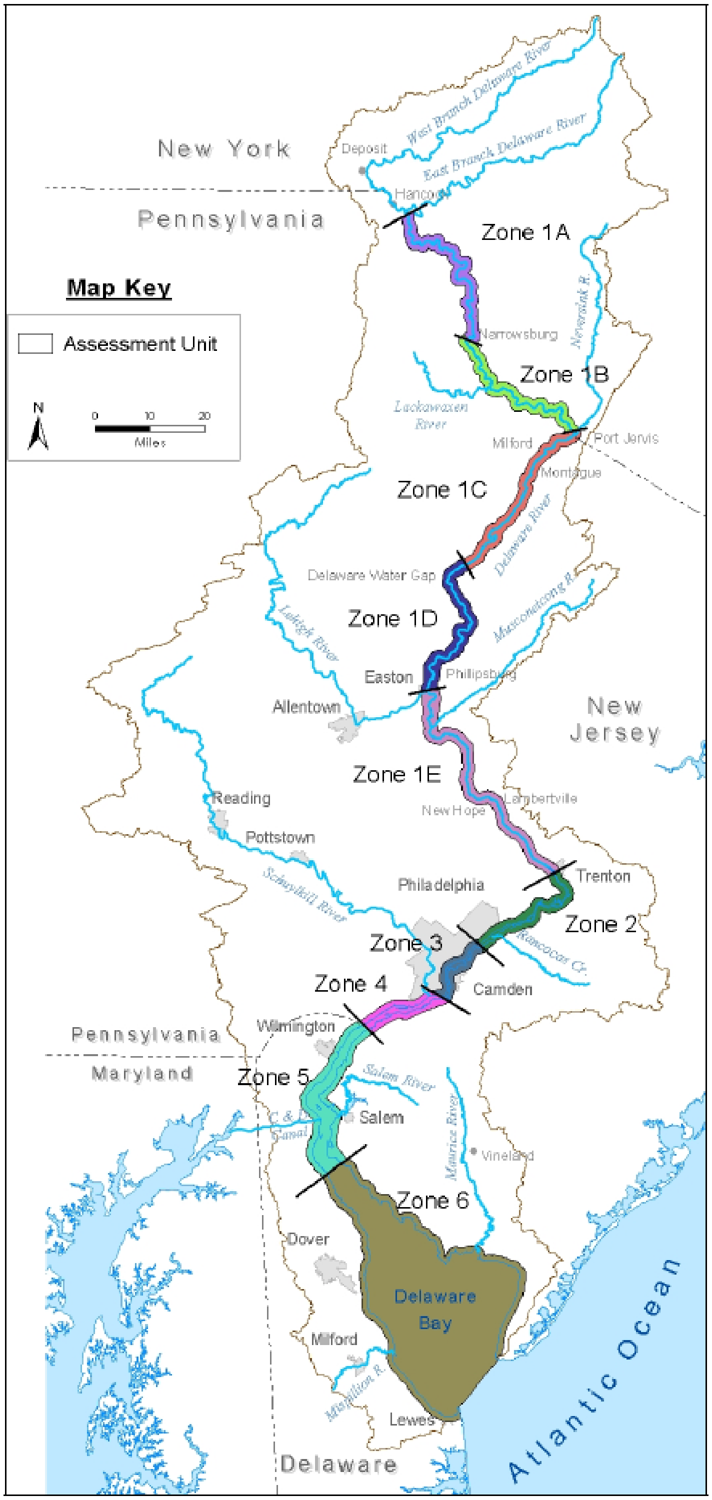

FIGURE 4: Delaware River water quality management zones (DRBC 2010)

During the 1960s when the river was anoxic and a decade before the 1970s Clean Water Act Amendments, the DRBC adopted the first interstate water quality standards and imposed waste load allocations on 80 dischargers. The Federal Water Pollution Control Administration (1966) and the Harvard Water Program (Dorfman et al.,1972, Maass et al., 1962, Reuss, 1973, and Schaumberg, 1967) issued a first-ever economic report that concluded water supply and recreation benefits due to improved water quality in the Delaware River would exceed water pollution control costs (Thoman 1972, Kneese and Bower 1984, and Johnson 1967). The 1966 FWPCA study estimated pollutant reduction costs necessary to sustain the diadromous fishery ranged from $150 million to achieve a DO level of 2.5 mg/l to $490 million to achieve DO criteria of 4.5 mg/l with diminishing marginal costs of improvement occurring at DO of 3.0 mg/l (Table 3 and Figure 5). Thoman (1972) estimated that if DO improved from 0.5 mg/l in 1964 during a 25-year drought to a future level of 3.0 mg/l, then shad passage would achieve 80% survival. In 1968, the DRBC anticipated (successfully as it turns out four decades later) that the waste load abatement plan would remove 85%-90% of carbonaceous BOD and eventually boost DO from near zero to 4 mg/l at Philadelphia (Figure 6). In 1967, the DRBC considered this benefit-cost analysis and set the current DO standard of 3.5 mg/l in the Delaware River near Philadelphia to support spring and fall migration of anadromous fish.

TABLE 3. Costs to Meet Water Quality Objectives in the Delaware Estuary (FWPCA 1966)

Objective Set	**DO Criteria (mg/l)**	**BOD/COD Residual (lb/day)**	**% Pollution Removal**	**Total Costs ($1964) ($ million)**	**Marginal Costs ($1964) ($ million)**	**% Survival Shad Passage**
I.	4.5	100,000	92%-98%	490	160-260	
II.	4.0	200,000	90%	230-330	100-150	90%
III.	3.0	500,000	75%	130-180	30-30	80%
IV.	2.5	500,000	50%	100-150	70-120	
V.	0.5	status quo		30	0	20%

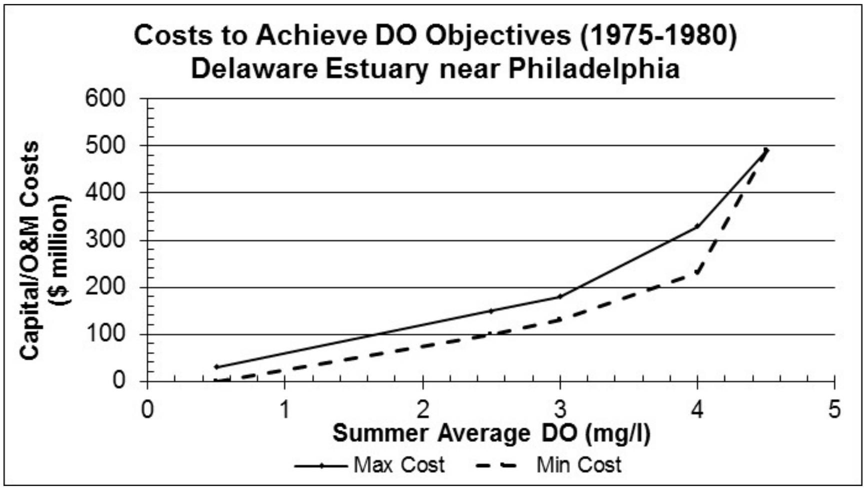

FIGURE 5. Costs to Achieve Dissolved Oxygen Objectives in the Delaware Estuary

(FWPCA 1966, Kneese and Bower 1984)

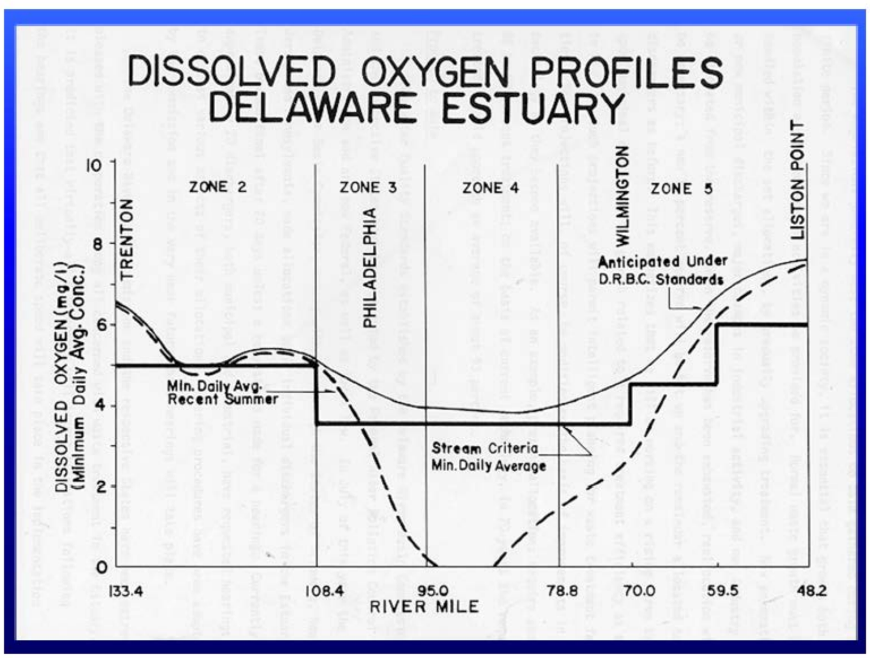

FIGURE 6. DRBC Dissolved Oxygen Criteria along the Delaware Estuary in 1968.

DO levels in the Delaware Estuary vary by water temperature, sunlight, winds, and pollutant loads (Gilbert et al. 2010). By 2010, DO levels in the Delaware River at Ben Franklin Bridge mostly exceeded the criteria except for violations below 3.5 mg/l during the hot months of June through August (Figure 7). Less than 0.5% of readings since 2000 did not meet the 3.5 mg/l criteria, primarily during the warm summer. In July and August, DO in the Delaware River at Philadelphia periodically declines below the 3.5 mg/l criteria (46% DO saturation) when water temperatures approach 30° C or 86° F (Figure 8). At 30°C, just a little bit of BOD loading will depress DO from 100% saturation at 7.54 mg/l to 80% saturation at 6 mg/l. Therefore, a future DRBC DO standard much higher than 5 mg/l (66% saturation) or 6 mg/l (80% saturation) may prove difficult to achieve given the quite warm water temperatures that occur during summer.

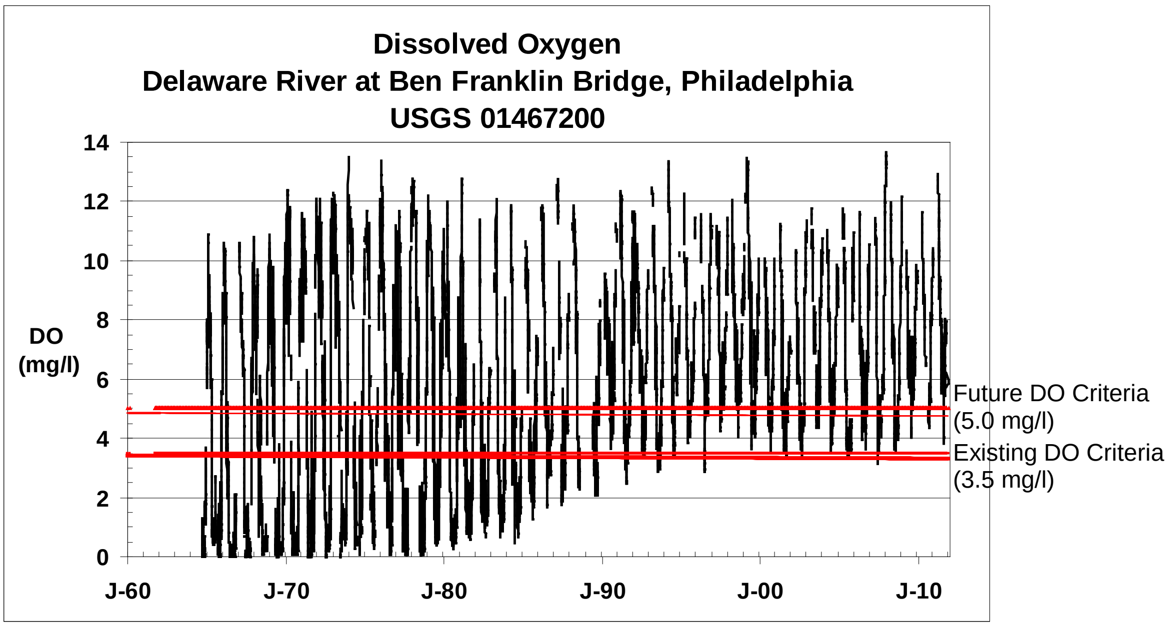

FIGURE 7. Mean Daily Dissolved Oxygen at Ben Franklin Bridge along Delaware River

Scientists on the Delaware Estuary Science and Technical Advisory Committee (STAC) have recommended that DRBC raise the fishable DO standard to at least 4.0, 5.0, or perhaps 6.0 mg/l in Zone 4 from Philadelphia to Wilmington given the literature suggests the current DO criteria of 3.5 mg/l is too low to support year-round survival of anadromous shad and sturgeon (Ad-Hoc Task Force 1979, Delaware River Fish and Wildlife Management Cooperative 1982, Delaware Estuary Use Attainment Project 1989, and PDE STAC 2014). Juvenile Atlantic sturgeon may suffer over 50% mortality at 25° C (77° F) when DO is 3.5 mg/l (Secor and

Gunderson 1998). Juvenile shortnose sturgeon are prone to 50% mortality when DO declines below 3.0 mg/l at 25° C (Campbell and Goodman 2004).

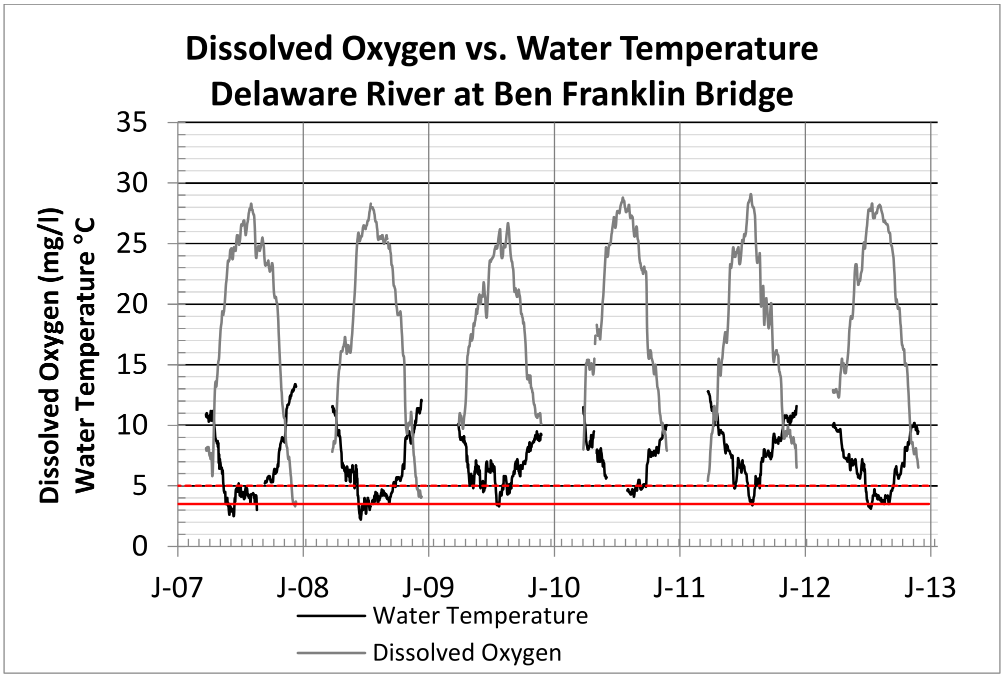

FIGURE 8. Water Temperature/Dissolved Oxygen along the Delaware River (www.usgs.gov)

A policy change to adopt more stringent DO water quality criteria would have economic implications. A watershed restoration program that reduces nutrient pollution would improve water quality and boost the clean water economies of the tourism, recreation, hunting/fishing, real estate, and water treatment sectors. But how much will it cost to reduce nutrient pollutant loads and improve water quality to a higher, more protective DRBC dissolved oxygen standard?

METHODS

This research estimates the 21st century costs of nitrogen pollutant load reductions necessary to increase dissolved oxygen from current criteria (3.5 mg/l) to a future, more stringent water quality standard (5.0 or 6.0 mg/l) in the Delaware River. The most cost-effective N reduction options are identified by minimum costs to obtain the desired water quality goal assuming marginal costs of all possible measures are equal. To estimate the most cost-effective combination of nitrogen load reductions, this research followed these methods: (1) quantify nitrogen loads from the Delaware Basin for atmospheric, urban/suburban, wastewater, and agricultural sources, (2) utilize total maximum daily load (TMDL) models to estimate pollutant load reductions needed to improve DO in the Delaware River from current 3.5 mg/l to future more protective standard, (3) define best management practices (BMPs) to reduce N loads from point/nonpoint sources and estimate unit N load reduction costs ($/lb N/yr), (4) estimate costs of N load reductions (lb/yr) to improve DO levels in the tidal Delaware River for various BMP options ranging from least to maximum cost and (5) construct marginal abatement cost curves to define least costs to improve DO to more stringent fishable criteria. Section 305b of the Federal Clean Water Act requires states to develop TMDL's if a stream is listed as impaired for a pollutant such as nutrients. The TMDL is the maximum amount of a pollutant discharged to a stream without violating water quality standards.

TMDL = PS + NPS + FS, where:

TMDL = Maximum pollutant load (lb/yr) to stream without violating water quality standards.

PS = Sum of point source pollutant loads (lb/yr) from wastewater discharges.

NPS = Nonpoint source loads (lb/yr) from atmospheric, agriculture, stormwater sources.

FS = Factor of safety (10% to 25%) to account for monitoring and modeling variance.

1. Nitrogen Loads: Estimate annual nitrogen loads (lb/yr) in the Delaware Basin in Delaware, New Jersey, New York, and Pennsylvania using the USGS SPAtially Referenced Regressions on Watershed (SPARROW) model (Moore et al. 2011). The SPARROW model (Moore et al. 2011) indicates the Delaware River watershed delivers the highest unit N load (4.3 ton/mi^2/yr) and second highest nitrogen load (50,525 ton/yr) of any river basin along the Atlantic

Coast of the U.S. (Table 4). SPARROW estimates N loads for base year 2002 from point sources (wastewater discharges) and nonpoint sources (atmospheric deposition, agriculture fertilizer/manure, and urban/suburban land) and accounts for watershed characteristics such as precipitation, temperature, soil permeability, stream density, flow rate, velocity and lake/reservoir hydraulics (Alam and Goodall 2012). SPARROW N load estimates are calibrated with EPA STORET water quality monitoring data and are well correlated as coefficients of determination (r^2) are 0.83 for yield and 0.97 for load which explains 83% to 97% of the variance between the predictive model and observed water quality data.

TABLE 4. SPARROW Nitrogen Loads in Atlantic Coast River Basins (Moore et al. 2011)

River Basin	**Drainage Area (mi^2)**	**Nitrogen Load (ton/yr)**	**Unit N Load ($ton/mi^2/yr$)**
Susquehanna	27,490	73,040	2.7
Delaware	11,819	50,525	4.3
Potomac	14,658	44,707	3.0
Hudson	13,363	28,711	2.1
James	10,339	17,482	1.7
Connecticut	11,261	17,236	1.5
Merrimack	5,000	9,068	1.8
Kennebec	9,564	7,539	0.8

The USGS SPARROW model simulates nitrogen removal based on hydrological and biogeochemical processes such as denitrification, particulate settling, water velocity, and depth (Preston et al. 2011). Instream fractional N removal declines with increased water depth and stream size. Watersheds with climates that have lower temperatures and higher precipitation deliver greater nitrogen loads to streams. Based on the delivery fraction of nitrogen (i.e. proportion of nitrogen load delivered to the outlet) implementation of BMPs in watersheds closest to the Delaware Estuary would provide the most immediate improvements in water quality (Figure 9). Conversely, nitrogen yields from watersheds far from the estuary (i.e. headwaters of the upper Lehigh and Schuylkill) are less likely to influence water quality in the

Delaware Estuary. The SPARROW model suggests the tributaries provide significant nitrogen attenuation benefits as these rivers flow downstream to the Delaware Estuary.

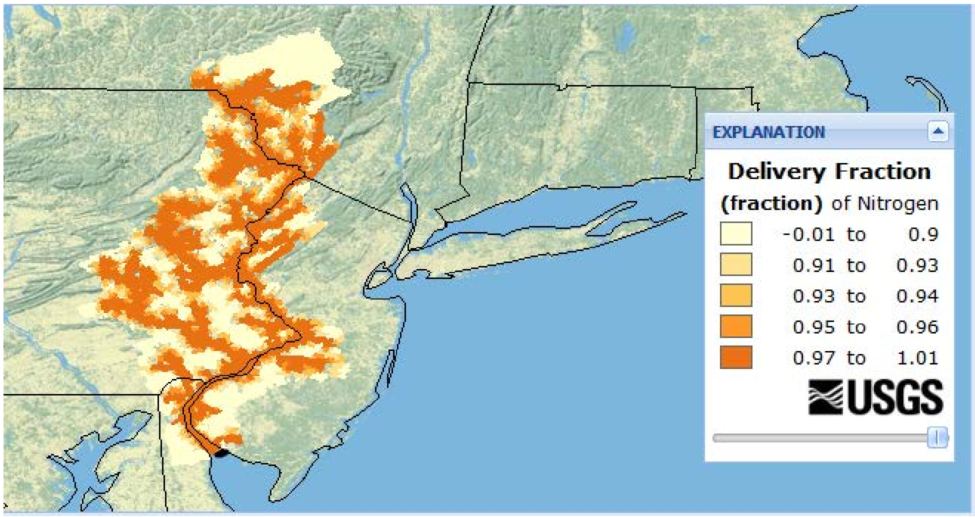

FIGURE 9. Delivery Fraction of Nitrogen in the Delaware Basin from USGS SPARROW model

2. N Load Reductions: Define nitrogen load reductions (lb/yr) to improve water quality to meet a future DRBC 5.0 mg/l DO standard in the tidal Delaware River between Philadelphia and Wilmington. The EPA Water Quality Analysis Simulation Program (WASP), USGS Hydrological Simulation Program-Fortran (HSPF), and Generalized Watershed Loading Function (GWLF) were examined to estimate TMDL pollutant load reductions in the lower Delaware Basin (EPA 2000). These hydrodynamic models suggest that "better-than-secondary" treatment was necessary to meet a more stringent DO water quality standard of 5 mg/l in the Delaware River below Philadelphia. A survey of 15 TMDL models by Scatena et al. (2006) in the lower Delaware River suggests that achieving a DO target of 5.0 mg/l would require a 32% (median) reduction in nitrogen within a range from 20% (25^{th} percentile) to 48% (75^{th} percentile) reduction (Figure 10). By comparison the Brandywine-Christina watershed TMDL model requires a 38% reduction in nitrogen loads to meet a dissolved oxygen water quality standard of 5 mg/l in the watershed that contributes 8% of the N load to the Delaware Estuary (EPA 2006).

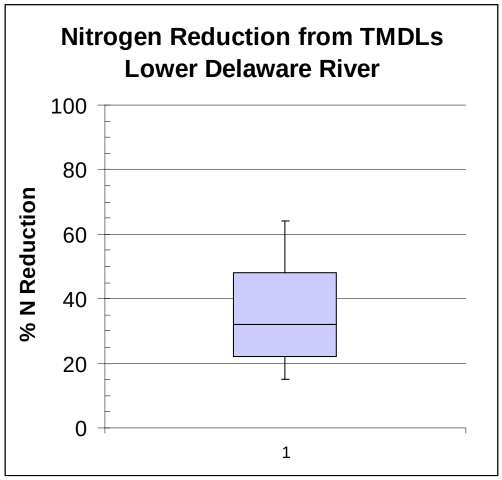

FIGURE 10. Nitrogen Load Reductions from TMDL Models for the Lower Delaware River (Scatena et al. 2006)

3. BMP Costs: Derive unit costs of N load reductions ($/lb N reduced) for point source BMPs such as wastewater treatment and nonpoint source BMPs such as atmospheric motor vehicle exhaust controls and power/industrial plant scrubbers, urban/suburban retrofitting, stream restoration, wet ponds, stormwater wetlands, and agricultural practices such as no till, cover crops, forest buffers, and animal waste management (Table 5)

TABLE 5. Nitrogen Reduction Best Management Practices (EPA 1993)

Nitrogen Source	Best Management Practice (BMP)
Wastewater Treatment Plant	Nutrient Reduction Technology
Atmospheric Deposition	Motor vehicle exhaust controls
	Power/industrial plant scrubbers
Agricultural Conservation	Ag Nutrient Management Plans
	Conservation Tillage
	Cover Crops
	Diversions
	Forest Buffers
	Grass Buffers
	Terraces
Urban/Suburban Stormwater	Wet Detention Pond
	Grass Swale
	Infiltration Basin
	Septic System Replacement
	Stormwater Wetland
	Vegetated Filter Strip

Nitrogen reduction costs ($/lb N) vary from $1.20-$11.0 N for agricultural conservation, $8.56- $79.00 for wastewater treatment, $75.00-$132.00 for airborne emissions controls, and $90.00-$500.00 for urban/suburban stormwater retrofit BMPs (Table 6). Wastewater treatment N load reduction costs vary from $8.56-$27.65 in the Chesapeake Bay watershed (Chesapeake Bay Program 2004) to $17.30 in the Connecticut River Basin (Evans 2008) and $63.00-$79.00 in Maine and New Hampshire (Jones et al. 2010, Trowbridge 2010). Airborne deposition nitrogen load reduction costs in the Chesapeake Bay range from $75.00 for Clean Air Act programs (Jones et al. 2010) to $132.00 for low emission vehicle programs (EPA 206 and Jones et al. 2010). Urban stormwater retrofitting is an expensive option with costs that range from $90 to $500/lb N reduced (EPA 2000, CBP 2004, Weiland 2009, and Jones et al. 2010).

Agricultural conservation practices can reduce N loads by 40% for grass buffers to 90% for cover crops at unit costs ($/ib N/yr) ranging from $1.20 for forest buffers to $10.11 for cover crops (EPA 2000, Weiland 2009, Evans 2008, Chesapeake Bay Program 2004, and Jones et al. 2010). Agricultural nutrient management plans can reduce N by 20% at a cost of $1.66 to $4.41. Conservation no-till cropping can reduce N by 55% at a cost of $1.57 to $3.20/lb N reduced. Winter cover crops reduce N by 90% at a cost of $4.39 to $10.11. Forest buffers remove 50% of N at $1.20 to $6.79. Grass buffers remove 40% of N at $1.67 to 6.76.

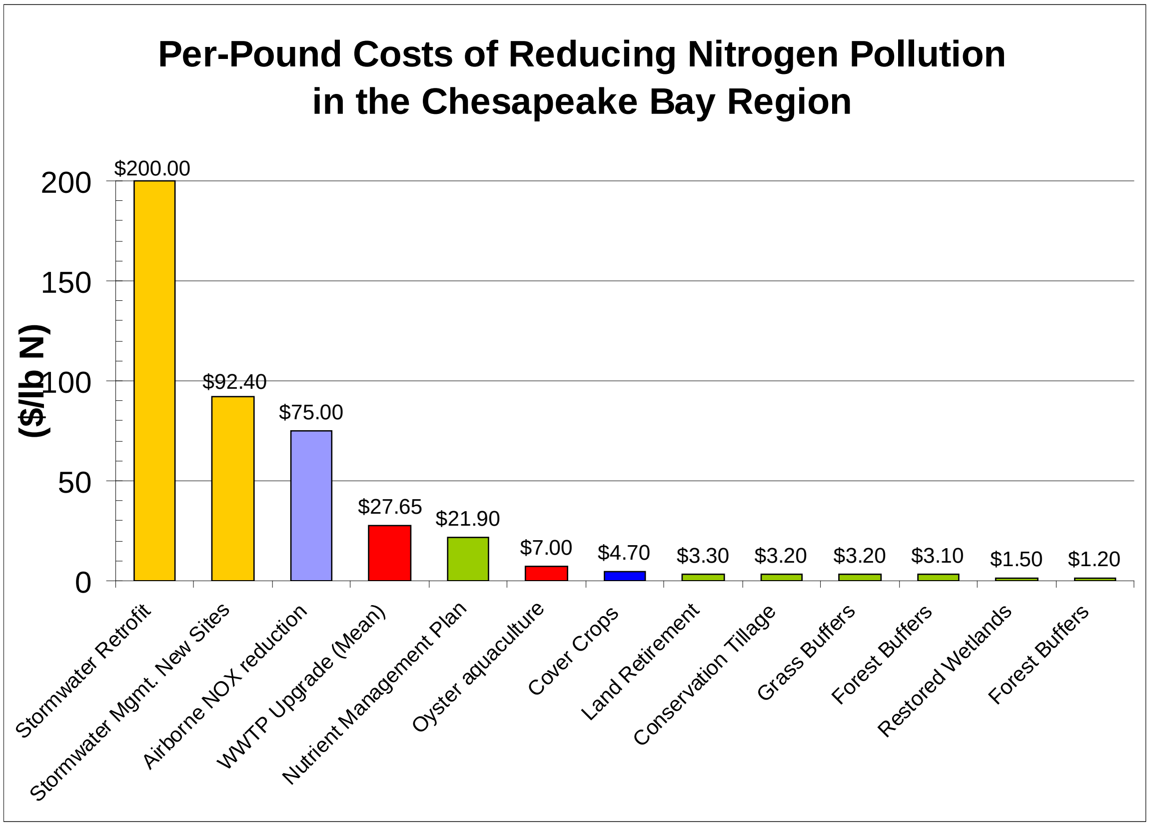

FIGURE 11. Costs ($2010) to Reduce Nitrogen Pollution in the Chesapeake Bay Region

(Jones et al. 2010, Chesapeake Bay Program and World Resources Institute)

TABLE 6. Nitrogen Reduction Costs by Source

Location	Source	Atmospheric Deposition ($/lb N)	Wastewater Treatment ($/lb N)	Urban/Sub. Stormwater ($/lb N)	Agriculture Conservation ($/lb N)
Chesapeake Bay	Jones et al. 2010	75	27.65	200-500	1.20-4.70
New Hampshire	Trowbridge 2010		63.00-79.00		
Connecticut R.	Evans 2008		17.30	137	4.93
Iowa	USDA NRCS			90	2.00-11.00
Chesapeake Bay	Chesapeake Bay Program 2004		8.56	>100	1.57-4.41
United States	EPA 1996	75-132			
Maryland	Weiland NOAA 2009			104-210	1.57-10.11

Costs to reduce nitrogen loads by 20% (25th percentile) 32% (median), and 48% (75th percentile) to meet a more stringent DRBC dissolved oxygen standard are calculated by multiplying N load reduction rates (lb/yr) by the unit cost ($/lb N reduced) in $2010 for atmospheric NOX reduction ($75.00/lb), wastewater treatment ($28.00/lb), agriculture ($5.00/lb), and urban/suburban ($200/lb) BMPs (Figure 11). By value transfer principles, nitrogen load reduction costs from the Chesapeake Bay watershed are appropriately translated to the Delaware River watershed since the two adjacent watersheds share similar climate, soils, topography, physiography, and hydrogeology.

4. Total N Reduction Costs: Estimate costs to reduce N loads by median 32% by maximizing load reductions from least cost agriculture and wastewater sources for 5 options.:

Option 1 - Reduce nitrogen loads equally by median 32% from all sources (agriculture, wastewater, atmospheric, and urban/suburban stormwater.

Option 2 - Reduce nitrogen loads from agriculture by 32%, wastewater by 47%, atmospheric deposition by 5%, and urban/suburban stormwater by 5%.

Option 3 - Reduce nitrogen loads from agriculture by 60%, wastewater by 29%, atmospheric deposition by 5%, and urban/suburban stormwater by 5%.

Option 4 - Reduce nitrogen loads from agriculture by 75%, wastewater by 20%, atmospheric deposition by 5%, and urban/suburban stormwater by 5%.

Options 5 - Reduce nitrogen loads from agriculture by 90%, wastewater by 10%, atmospheric deposition by 5%, and urban/suburban stormwater by 5%.

5. Marginal Abatement Cost: Construct nitrogen marginal abatement cost (MAC) curves (Van Soesbergen et al. 2007) to determine cost effective N load reductions to improve water quality by raising DO in the Delaware River to more stringent fishable criteria. Marginal cost curves show the change in cost compared with the change in reduced pollutant loads (Brown 1999). The MAC curve is constructed by plotting pollutant load reductions (lb/yr) for the practices and the annual costs of these measures. The MAC curves are constructed by plotting N load reduction costs ($/yr) on the horizontal axis and 25th, 50th (median), and 75th percentile N load reductions (lb/yr) on the vertical axis. The MAC curve illustrates relatively inexpensive measures on the left and more expensive measures to the right.

RESULTS

The USGS SPARROW model (Moore et al. 2011) indicates the highest nitrogen loads in the Delaware River watershed are delivered in the Schuylkill River and Brandywine Christina watersheds in southeastern Pennsylvania (Figure 12). The SPARROW model utilizes land cover data to predict nitrogen loads from urban/suburban and agricultural runoff. In 2006, the Delaware Basin was covered by 63% forest/wetlands, 20% agriculture, and 17% urban/suburban land (Figure 13). Pennsylvania covers 51%, New Jersey and New York each cover 21%, and Delaware covers 8% of the Delaware River Basin.

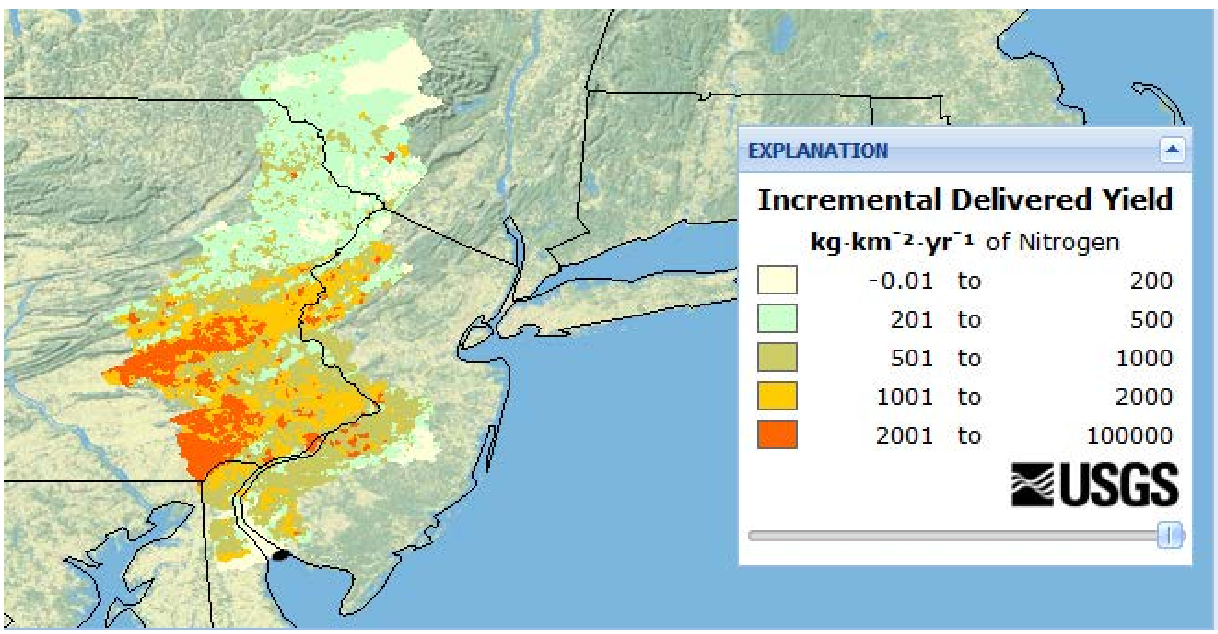

FIGURE 12. Incremental delivered nitrogen yield to Delaware Basin from SPARROW model

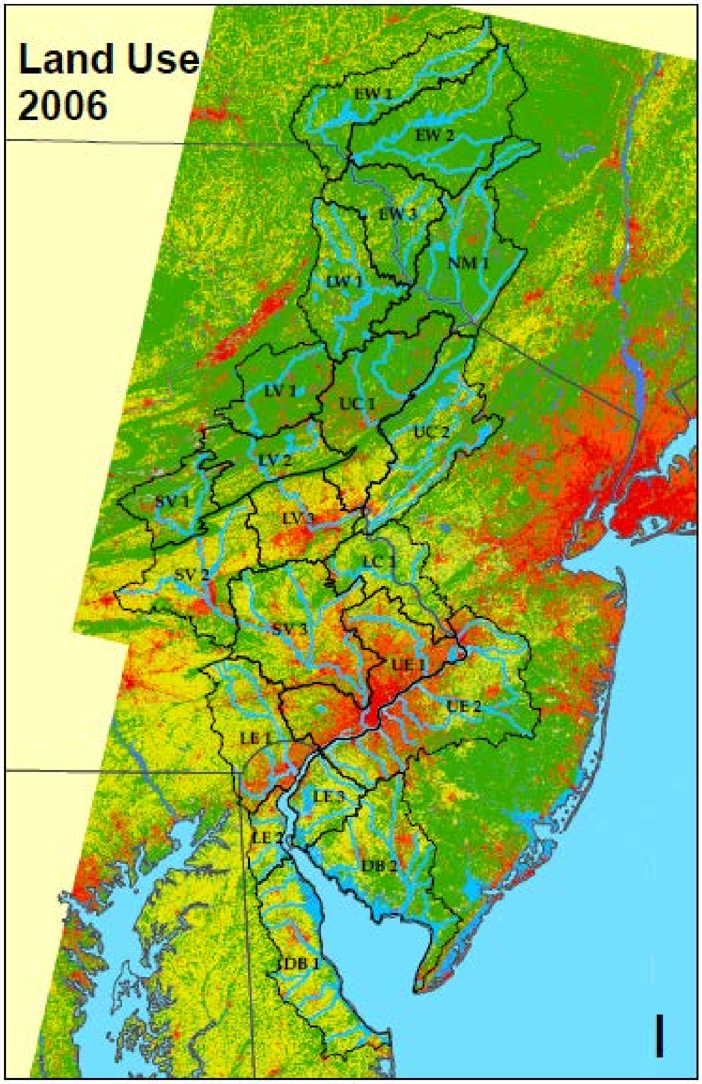

FIGURE 13. Land Use in the Delaware Basin, 2006 (NOAA CSC)
Land uses: forest (green), wetlands/water (blue), urban/suburban (red), agriculture (yellow)

In the Delaware Basin, the SPARROW model estimates almost half (46%) of the nitrogen flows from wastewater discharges and a third (29%) emanates from agriculture fertilizer/manure runoff (Figure 14). Urban/suburban stormwater (14%) from the cities and suburbs delivers just over 10% of the N load. The airshed of Delaware River is 10 times larger than its watershed and atmospheric deposition from industries and vehicles contributes 12% of the nitrogen to the estuary. Together Pennsylvania and New Jersey discharge over 90% of the nitrogen to the

Delaware Basin with half from wastewater discharges and a quarter to a third from agriculture (Figure 15). New York and Delaware contribute 4% and 3% of the nitrogen.

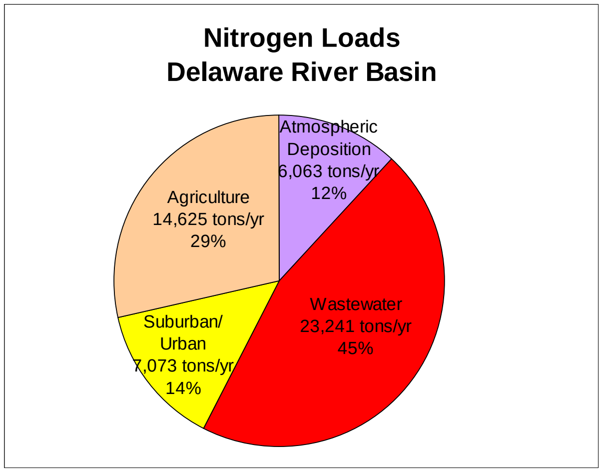

FIGURE 14. Annual Nitrogen Loads by Source in the Delaware Basin (Moore et al. 2011)

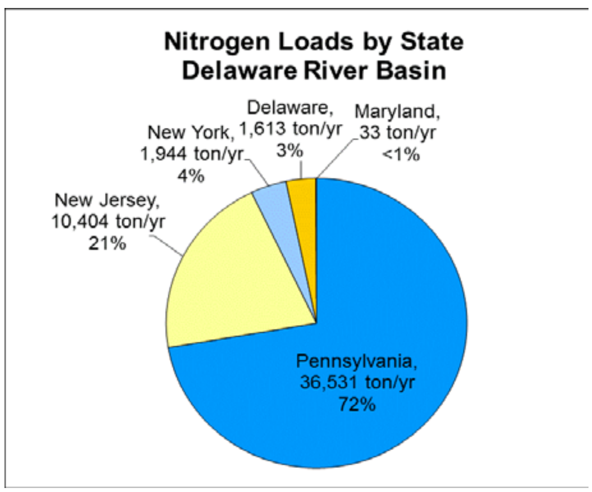

FIGURE 15. Annual Nitrogen Loads by State in the Delaware Basin (Moore et al. 2011)

Three watersheds – the Delaware River at Trenton, Schuylkill River, and above Philadelphia tributaries - deliver 80% of the nitrogen load to the estuary (Figure 16). Above Trenton, the Lehigh River contributes 9% of the N load to the Delaware River. Below Philadelphia; the Brandywine/Christina, Delaware River above Wilmington, and Delaware Estuary at Prime Hook watersheds each contribute 7%, 8%, and 3% of the N loads, respectively. Wastewater discharges are the predominant sources of N in the Delaware River above Philadelphia (82%), Schuylkill

(46%), and above Wilmington (68%) watersheds. Agriculture is the primary N source in the Delaware River at Trenton (34%), Brandywine-Christina (77%), and Delaware Bay at Prime Hook (72%) watersheds and second highest N source in the Schuylkill watershed (35%).

Observed N loads at USGS gages compare closely with modeled loads from SPARROW (Trench et al. 2012). The observed N load at the Delaware River at Port Jervis is 4.3 million lb/yr versus 6.1 million lb/yr predicted by SPARROW. The observed N load at Delaware River at Trenton is 31.2 million lb/yr compared to 25.1 million lb/yr from SPARROW. Along the Schuylkill, the observed N load is 20.8 million lb/yr versus 28.9 million lb/yr from SPARROW.

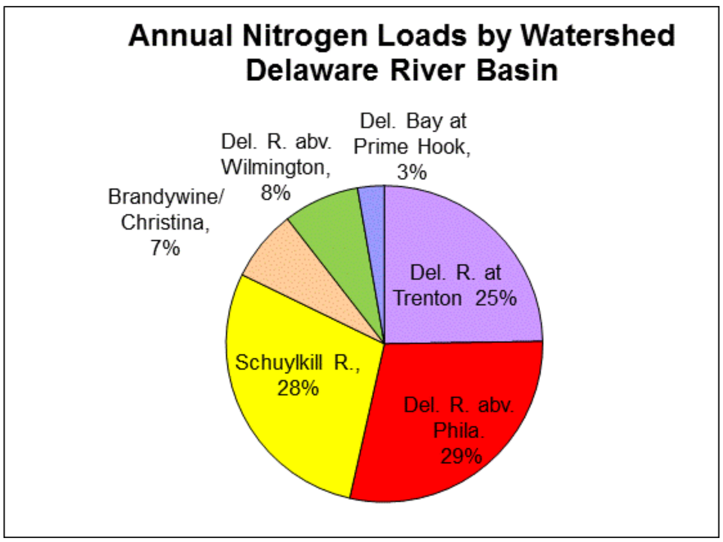

FIGURE 16. Annual Nitrogen Loads by Watershed in the Delaware Basin (Moore et al. 2011)

Under Option 1, to meet Delaware River TMDLs nitrogen loads must be reduced by 16,168 tons/yr (32.3 million lb/yr) to achieve 32 % reductions applied equally to all sources (Table 7). Under this uniform load reduction scenario, wastewater N loads are reduced by 7,437 tons/yr followed by agriculture (4,689 tons/yr), urban/suburban (2,264 tons/yr), and atmospheric reduction (1,940 tons/yr). The cost to reduce N loads evenly by 32% for each source is $1.66 billion/yr with the largest costs borne by urban/suburban stormwater retrofitting ($905 million/yr) with the highest unit cost $200/lb N followed by wastewater discharge ($416 million/yr), atmospheric NOX reduction ($291 million/yr), and agriculture conservation ($47 million) with the lowest unit cost of $5/lb N reduced. According to Option 1, to reduce N equally by 32% from all sources, loads must be reduced by 11,690 ton/yr in Pennsylvania for $1.2 billion, 3,329 ton/yr in New Jersey for $317 million, 622 ton/yr in New York for $95 million, 516 ton/yr in Delaware for $60 million, and 12 ton/yr in Maryland for $700,000.

The TMDL models suggest that nitrogen loads should be reduced by a median 32% within a range of 20% (25th percentile) to 48% (75th percentile) to increase DO levels from the current DRBC criteria (3.5 mg/l) to meet a future standard (5.0 mg/l) in the Delaware River. By maximizing least cost agricultural and wastewater BMP options and minimizing higher cost airborne emissions and urban stormwater BMPs (Figure 17), annual costs to reduce N loads by 32% in the Delaware Basin are cut from $1.66 billion for Option 1 (reduce loads evenly for all sources) to $845 million for Option 2 (reduce Ag N by 32%), $652 million for Option 3 (reduce Ag N by 60%), $552 million for Option 4 (reduce Ag N by 75%), and $449 million for Option 5 (reduce Ag N by 90%). The least cost (Option 5) would reduce N loads by median 32% (32 million lb/yr) by reducing atmospheric NOX by 5%, wastewater N by 10%, urban/suburban N by 5%, and agricultural N by 90%. Annual costs range from $334, $449, and $904 million to reduce N loads by 20% (25th percentile), 32% (median), and 48% (75th percentile), respectively.

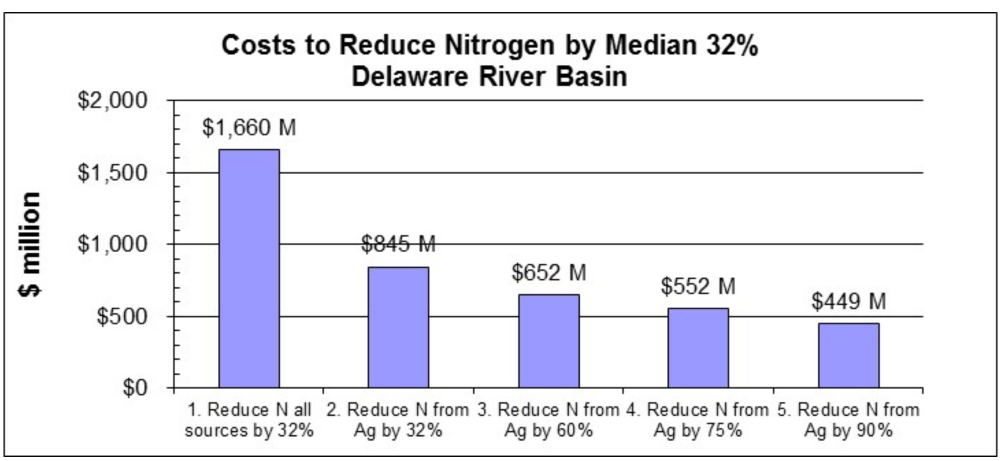

FIGURE 17. Costs ($2010) to Reduce Nitrogen Loads by 32% in the Delaware Basin

According to Option 5, the annual least cost to reduce N loads by 32% in the Delaware Basin is $449 million including $141 million for urban/suburban retrofitting, $132 million for agriculture conservation, $130 million for wastewater treatment, and $45 million for atmospheric NOX reduction (Figure 18). Covering half of the Basin, Pennsylvania's annual share is $322 million or 72% of the N load reduction cost (Figure 19). New Jersey would bear $87 million or 19% of the cost. New York State would contribute $19 million or 4% of the N reduction cost. Delaware would assume $16 million or 4% of the cost. Maryland's share would be $337,000.

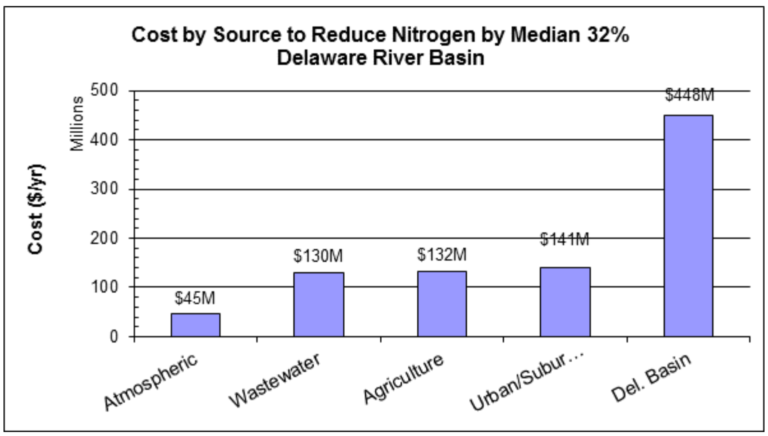

FIGURE 18. Least Cost ($2010) by Source to Reduce N loads by 32% in Delaware Basin

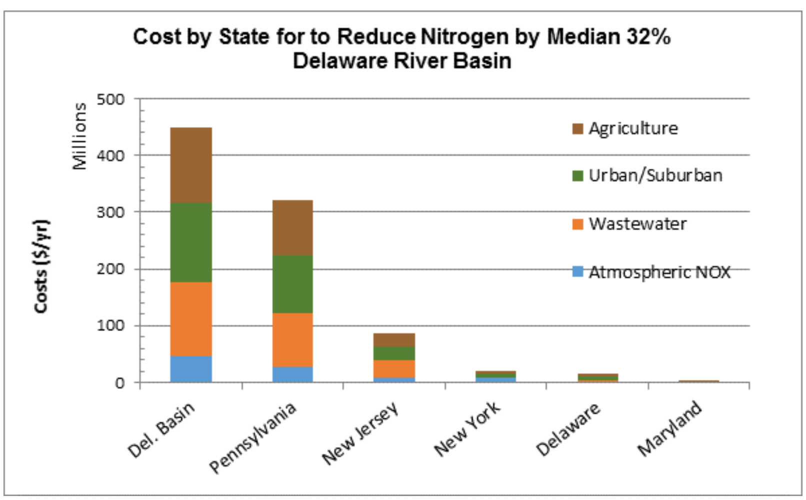

FIGURE 19. Least cost ($2010) by state to reduce nitrogen loads by 32% in Delaware Basin

TABLE 7. Least Cost ($2010) by State to Reduce Nitrogen by Median 32% in Delaware Basin

Basin/State	**Drainage Area (mi^2)**	**Nitrogen Reduction (32%) (ton/yr)**	**Atmospheric Deposition (5%) (ton/yr)**	**Wastewater Discharge (10%) (ton/yr)**	**Urban/ Suburban (5%) (ton/yr)**	**Agriculture Conservation (90%) (ton/yr)**
Del. Basin	11,819	16,168	303	2,324	354	13,187
Pennsylvania	5,987	11,982	183	1,680	256	9,863
New Jersey	2,461	3,007	52	551	62	2,341
New York	2,455	501	53	12	16	420
Delaware	908	602	7	56	16	523
Maryland	8	24	0	0	0	24
Basin/State	**Drainage Area (mi^2)**	**Nitrogen Reduction Cost ($M/yr)**	**Atmospheric Deposition ($75/lb N) ($M/yr)**	**Wastewater Discharge ($28/lb N) ($M/yr)**	**Urban/ Suburban ($200/lb N) ($M/yr)**	**Agriculture Conservation ($5/lb N) ($M/yr)**
Del. Basin	11,819	449	45	130	142	132
Pennsylvania	5,987	322	27	94	102	99
New Jersey	2,461	87	8	31	25	23
New York	2,455	19	8	0.6	6	4
Delaware	908	16	1	3	6	5
Maryland	8	0.3	0.02	0	0.08	0.2

On a watershed basis, the Delaware River at Trenton contributes 25% of the nitrogen load predominately from agricultural sources for $132 million or 30% of the total cost (Figure 20 and Table 8). The Schuylkill contributes 30% of the N load mostly from wastewater and agricultural sources at a cost of $124 million or 28% of the total cost. The tributaries between Philadelphia and Trenton contribute 29% of the N load mostly from wastewater with a cost of $104 million or 24% of the total. The Brandywine/Christina watershed would cost $37 million (8% of the N load reduction cost) where over ¾ of the nitrogen flows from agriculture. The watersheds between Wilmington and Philadelphia would require $32 million or 7% of the total cost to reduce mostly wastewater N loads. The Delaware Bay watershed between Prime Hook and Wilmington would cost $13 million to reduce mostly agricultural N loads from Coastal Plain streams on either side of the bay.

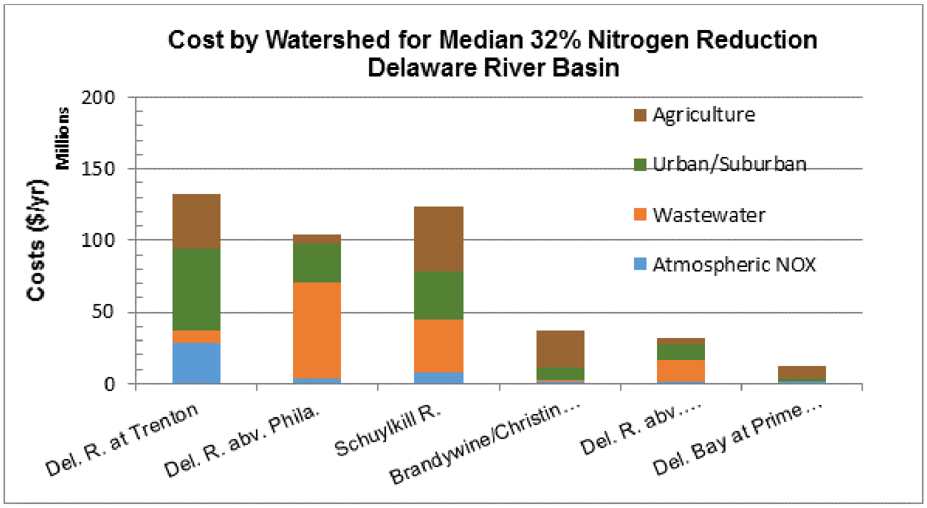

FIGURE 20. Least Cost by Watershed to Reduce Nitrogen Loads by 32% in the Delaware Basin

TABLE 8. Least Cost by Watershed to Reduce Nitrogen by Median 32% in the Delaware Basin

Basin/State	**Drainage Area (mi^2)**	**Nitrogen Reduction (32%) (ton/yr)**	**Atmospheric Deposition (5%) (ton/yr)**	**Wastewater Discharge (10%) (ton/yr)**	**Urban/ Suburban (5%) (ton/yr)**	**Agriculture Conservation (90%) (ton/yr)**
Del. R. at Trenton	6,846	4,299	188	165	143	3,804
Del. R. above Phila.	1,246	1,978	23	1,193	68	695
Schuylkill R.	1,894	5,410	54	663	81	4,612
Brandywine/Christina	561	2,618	13	17	20	2,568
Del. R. above Wilmington	488	775	9	265	28	473
Del. Bay at Prime Hook	732	912	9	10	5	887
Delaware Basin	**11,767**	**15,992**	**295**	**2,313**	**346**	**13,038**
Basin/State	**Drainage Area (mi^2)**	**Nitrogen Reduction ($mil/yr)**	**Atmospheric ($75/lb N) ($ mil/yr)**	**Wastewater ($28/lb N) ($ mil/yr)**	**Urban/Sub. ($200/lb N) ($ mil/yr)**	**Agriculture ($5/lb N) ($ mil/yr)**
Del. R. at Trenton	6,846	132	28	9	57	38
Del. R. above. Phila.	1,246	104	3	67	27	7
Schuylkill R.	1,894	124	8	37	33	46
Brandywine/Christina	561	37	2	1	8	26
Del. R. above Wilmington	488	32	1	15	11	5
Del. Bay at Prime Hook	732	13	1	1	2	9
Delaware Basin	**11,767**	**442**	**44**	**130**	**138**	**130**

Marginal abatement cost curves (Figures 21 and 22) illustrate the least costs to reduce nitrogen loads by median 32% within a range of 20% (25^{th} percentile) to 48% (75^{th} percentile). Based on the nitrogen MAC curve, 90% of the nitrogen (30 million lb N/yr) can be removed for just 35% ($160 million) of the $449 million total cost. The remaining 2 million lb N/yr) or 10% of the N load reduction will require 65% ($290 million/yr) of the total cost. Marginal abatement cost (MAC) curves define the most cost effective combination of nitrogen reduction strategies to improve DO to a future DRBC standard to provide year-round propagation of anadromous fish. Least cost agriculture and wastewater treatment reductions would be implemented first in priority watersheds followed by higher cost atmospheric deposition and urban suburban runoff controls. After the less costly agricultural and wastewater BMPs are implemented, nitrogen reduction in the Delaware Basin becomes incrementally less cost-effective after 30% N reduction as the slope of the cost curve flattens. Increasingly higher investments in more costly atmospheric and urban/suburban controls provided a diminishing rate of return in terms of pollutant removal efficiency per dollar spent.

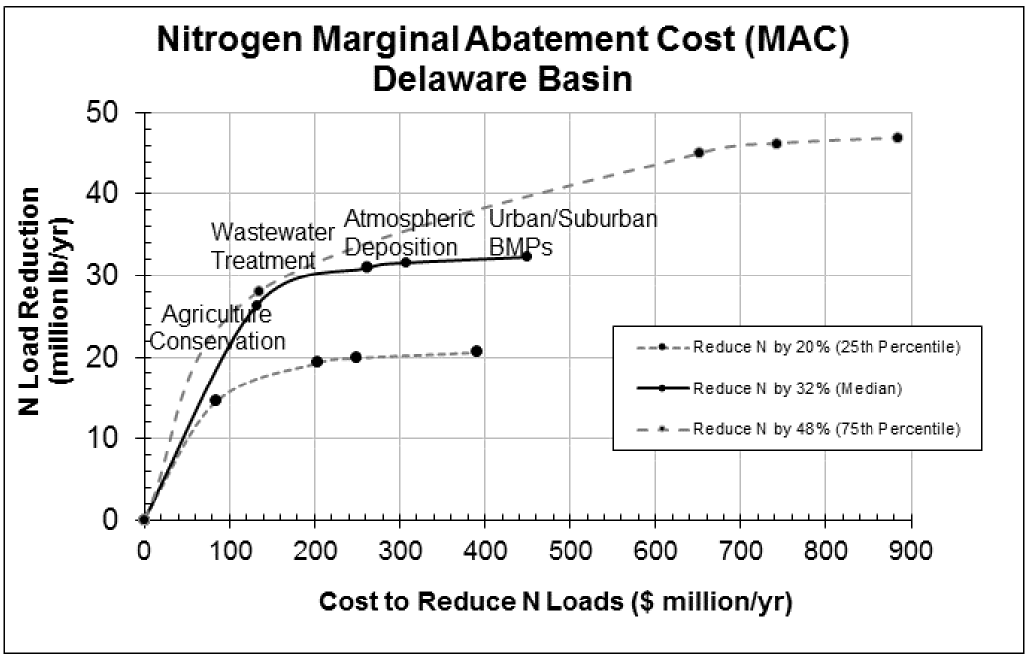

FIGURE 21. Nitrogen Marginal Abatement Least Cost Curves in the Delaware Basin

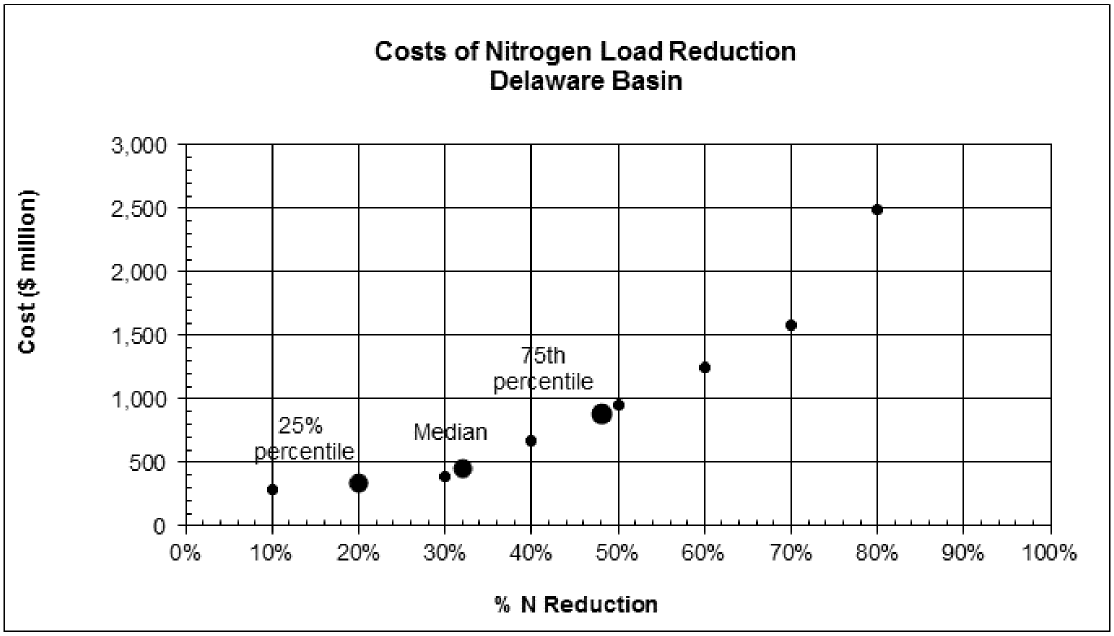

FIGURE 22. Nitrogen Reduction Cost Curve for the Delaware Basin ($2010)

DISCUSSION

Adjusting to 2010 dollars and starting from a base DO level of 3 mg/l, annual costs from the 1966 Delaware Estuary economic study range from $58-$87 million to achieve summer DO of 4.0 mg/l to $180-209 million to reach 4.5 mg/l (Table 9). These estimates from an economic study conducted fifty years ago correspond well with the 21st century least cost (Option 5) of $50 million to reach 4.0 mg/l, $150 million to reach 4.5 mg/l, and $449 million to reach 5.0 mg/l.

TABLE 9. Comparison of Costs to Meet Water Quality Criteria along the Delaware River

Objective	**Summer DO (mg/l)**	**Annual Costs ($2010 in millions)**	
		1966 Study[1]	**21st Century**
	5.0		449
I	4.5	180-209	150
II	4.0	58-87	50
III	3.0	0	0

1. FWPCA (1966) adjusted from $1964 to $2010 by 3% annually based on change in CPI.

The relationship between nitrogen load reduction (median 32%) and dissolved oxygen level to meet a future 5.0 mg/l DO standard in the Delaware River is assumed to be linear while the correlation is slightly curvilinear. This is important because a curvilinear trend in meeting the DO target may intersect the marginal cost curve differently than for a linear trend. Plots of pollutant load reduction and DO levels (Figure 23) from the 1960s economic study of the Delaware River indicate the coefficient of determination (r^2) for the linear measure of best fit (0.92) is similar to the r^2 for the curvilinear (exponential) regression (0.94). Since the linear and curvilinear regressions are nearly identical, the assumption of linear relationship between % N load reduction and DO levels in the Delaware River is adequate. Future work utilizing a future hydrodynamic model would improve on these pollutant load and DO relationships.

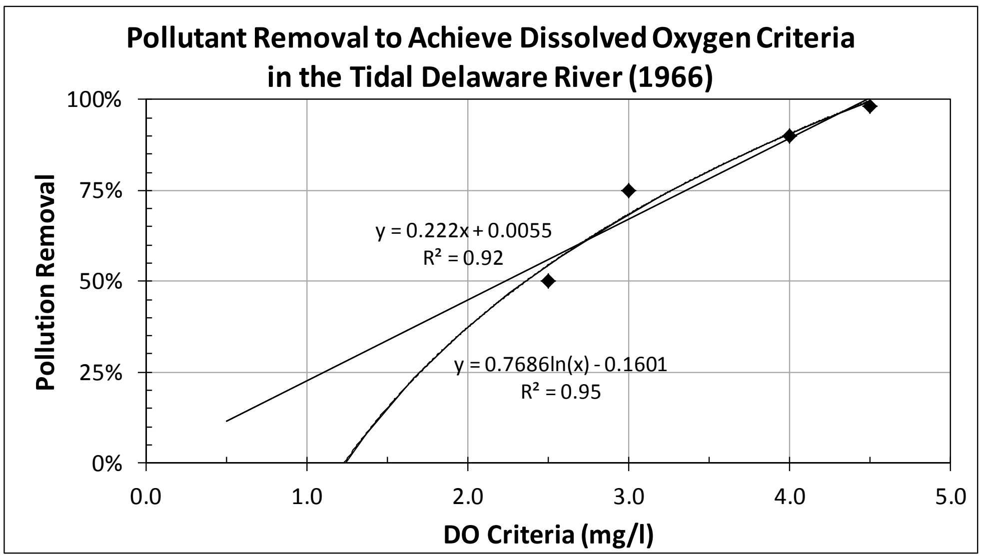

FIGURE 23. Pollutant Removal to Achieve DO criteria in the Delaware River near Philadelphia (FWPCA 1966)

An important consideration is the inverse relationship between dissolved oxygen saturation and water temperature (Figure 24). The costs and benefits of achieving improved water quality in the Delaware River through higher DO criteria assume that water temperatures peak near 30°C

(86°F) which usually occurs in July and August. At 30° C, freshwater DO saturation is 7.54 mg/l and DO is 46% saturated at 3.5 mg/l, 53% saturated at 4.0 mg/l, 60% saturated at 4.5 mg/l, 66% saturated at 5.0 mg/l, and 80% saturated at 6.0 mg/l. Should water temperatures in the tidal Delaware River increase by 2°C to peak summer levels of 30° C, based on saturation, DO levels will decline by about 0.2 mg/l without any decrease in nutrient loading. More research is needed utilizing a new hydrodynamic model would be helpful to explore the influence of water temperature and salinity on dissolved oxygen in the Delaware Estuary.

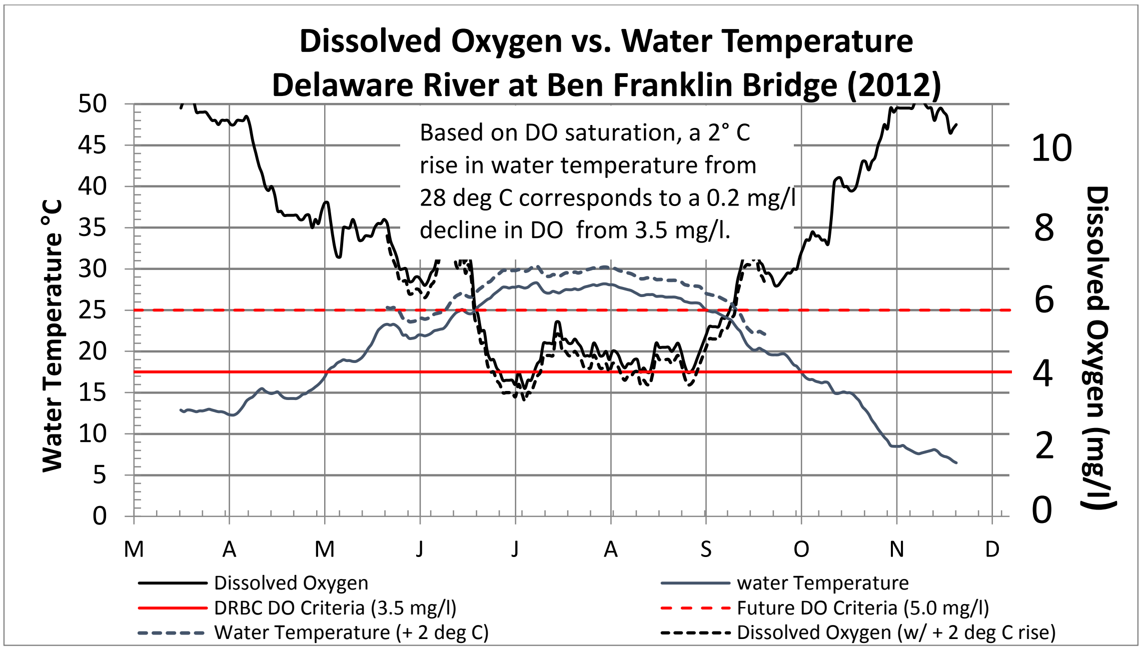

FIGURE 24. Dissolved oxygen/water temperature along the Delaware River at Ben Franklin Br.

Based on the delivery fraction of nitrogen (i.e. fraction of nitrogen load delivered to the outlet) implementation of BMPs in watersheds closest to the Delaware Estuary provide the most immediate improvements in water quality. The SPARROW model indicates the delivered yield of nitrogen from watersheds far from the estuary such as headwaters of the Delaware River in New York State and upper Lehigh and Schuylkill basins are less likely to influence DO levels in the Delaware Estuary. Nitrogen reduction practices should be cost effectively invested in watersheds that deliver the highest yield of nitrogen and are close to the estuary.

Groundwater can contribute significant nitrogen and phosphorus loads to surface waters. For instance, half of the nonpoint source N load to the Chesapeake Bay flows through groundwater and the other half flows via surface runoff (Phillips and Lindsey 2003). Depending on soil permeability, it could take years for nutrients such as N and P in groundwater to reach the Delaware Estuary from the source (Claessens et al. 2009). Implementation of nitrogen source controls for airborne emissions and wastewater treatment would have immediate effect on improved water quality in the Delaware River whereas urban suburban and agriculture BMPS could take months to years to make an impact on water quality depending on soils and the physiographic province (Table 10) The SPARROW model does not account for direct contributions of nitrogen from groundwater therefore it is likely that nitrogen loads to the Delaware Estuary are underestimated in this analysis. Additional modeling, particularly geographically resolved hydrodynamic modeling with explicit inclusion of groundwater transport is needed to address this quantitatively.

TABLE 10. Influence of travel time on improved water quality benefits in the Delaware River

Nitrogen Source Control	**Coastal Plain**	**Piedmont Province**	**Ridge and Valley**	**Appalachian Plateau**
Airborne Emissions	Immediate	Immediate	Immediate	Immediate
Wastewater Treatment	Immediate	Immediate	Immediate	Immediate
Urban/Suburban BMPs				
Surface Water Runoff	Months	Immediate	Immediate	Immediate
Groundwater Recharge	Years	Months to years	Months	Months
Agriculture Conservation				
Surface Water Runoff	Months	Immediate	Immediate	Immediate
Groundwater Recharge	Years	Months to years	Months	Months

CONCLUDING REMARKS

The Delaware River and its tributaries have made a notable recovery in the half-century since JFK signed the DRBC Compact in 1961, Richard Nixon formed the EPA in 1970, and Congress passed the Federal Clean Water Act Amendments during the 1970s. A first-of-its-kind 1966 benefit-cost analysis conducted by the Federal Water Pollution Control Administration (FWPCA) concluded that it would be cost-effective for the DRBC to fund a multi-million-dollar per year waste load abatement program to raise dissolved oxygen levels to boatable and fishable standards that would in turn generate economic activity. In 1967, the DRBC used this benefit-cost analysis to set DO criteria at 3.5 mg/l along the river from Philadelphia to Wilmington where this water quality standard has stood for over four decades. The FWPCA and DRBC were indeed prescient as multi-billion dollar investments in Delaware River water pollution control programs have boosted water quality as measured by dissolved oxygen from anoxia during the 1960s to levels that meet DRBC criteria of 3.5 mg/l most of the year except during the increasingly hot summers. With improved water quality, anadromous American shad and Atlantic sturgeon and striped bass have returned along with a growing river-based tourism, boating, fishing, and bird-watching recreation economy.

While the Delaware has made one of the most extensive recoveries of any estuary in the world, scientists have called for raising the DO standard from 3.5 mg/l that has stood since the 1960s to a higher level of protection. A more rigorous standard of at least 5 mg/l or 6 mg/l would provide for more year-round protection of anadromous fish such as the recovering American shad and the nearly extirpated Atlantic sturgeon (just placed on the Federal Endangered Species List). A more rigorous DO standard would also provide protection against atmospheric warming that is projected to increase water temperatures, raise sea levels, and elevate chloride levels, all of which act in combination to reduce DO saturation.

By maximizing least cost agricultural and wastewater BMPs and minimizing higher cost airborne emissions and urban stormwater retrofitting BMPs, annual costs to reduce N loads by 32% in the Delaware Basin are cut by more than 300%, from $1.66 billion for Option 1 (reduce

N equally from all sources by 32%) to $449 million for Option 5 (reduce Agriculture N by 90%). Nitrogen marginal abatement cost (MAC) curves show it to be more cost-effective to prioritize upstream investments in agricultural conservation and wastewater treatment as these controls have lower unit nitrogen reduction costs that are up to an order of magnitude less than the more expensive airborne emissions source control and urban/suburban best management practices. This 21st century economic analysis shows it to be cost-effective to prioritize agricultural conservation and wastewater treatment investments in the Delaware River watershed to reduce 90% of the pollutant load (30 million lb/yr of nitrogen) for $160 million at 35% of the estimated $449 million annual cost. The estimated annual cost to reduce nitrogen loads and increase DO to meet a more stringent standard in the Delaware River includes $45 million for atmospheric NOX reduction, $130 million for wastewater treatment, $132 million for agriculture conservation, and $141 million for urban stormwater retrofitting. In 2010 dollars, annual costs from the 1966 Delaware Estuary economic study range from $58-$87 million to achieve summer DO of 4.0 mg/l to $180-209 million to reach DO of 4.5 mg/l. These estimates from an economic study conducted 50 years ago correspond well with the 21st century least cost (Option 5) of $50 million to reach 4.0 mg/l, $150 million to reach 4.5 mg/l, and $449 million to reach 5.0 mg/l.

The financial need to restore the Delaware River is great. However, the Delaware is one of just a few river basins in the U.S. or the world that has a governance structure by authority of Federal/State compact to administer water pollution control programs using economic incentives.

LITERATURE CITED

Ad-Hoc Task Force to Evaluate Dissolved Oxygen Requirements of Indigenous Estuary Fish, 1979. Dissolved Oxygen Requirements of a "Fishable" Delaware River Estuary. Report to the Delaware River Basin Commission. Trenton, New Jersey.

Alam, M. J. and J. L. Goodall, 2012. Toward Disentangling the Effect of Hydrologic and Nitrogen Source Changes from 1992 to 2001 on Incremental Nitrogen Yield in the Contiguous United States, Water Resources Research. 48(4):1-16.

Albert, R. C, 1988. The Historical Context of Water Quality Management for the Delaware Estuary. Estuaries. 11(2):99-107.

Bain, M., M. T. Walter, T. Steenhuis, W. Brutsaert, and A. Gaetano, 2010. Delaware River and Catskill Region Hydrologic Observatory. Prospectus by the Cornell University Hydrologic Sciences Working Group. 10 pp.

Bricker, S., B. Longstaff, W. Dennison, A. Jones, K. Boicourt, C. Wicks, and J. Woerner, 2007. Effects of Nutrient Enrichment in the Nation's Estuaries: A Decade of Change. NOAA Coastal Ocean Program Decision Analysis Series No. 26. National Center for Coastal Ocean Science, Silver Spring, Maryland. 328 pp.

Campbell, J. G. and L. R. Goodman, 2004. Acute Sensitivity of Juvenile Shortnose Sturgeon to Low Dissolved Oxygen Concentrations. Transactions of the American Fisheries Society. 133(3):772-776.

Chesapeake Bay Program, 2004. Chesapeake Bay Watershed BMP Potential Load Reductions and Cost-effectiveness Study. Annapolis, MD: Chesapeake Bay Program.

Church, T. M., C. K. Sommerfield, D. J. Velinsky, D. Point, C. Benoit, D. Amouroux, D. Plaa, and O. F. X. Donard, 2006. Marsh Sediments as Records of Sedimentation, Eutrophication and Metal Pollution in the Urban Delaware Estuary. Marine Chemistry. 102:72–95.

Claessens, L., C. L. Tague, L. E. Band, P. M. Groffman, and S. T. Kenworthy, 2009. Hydro-ecological Linkages in Urbanizing Watersheds: An Empirical Assessment of In-stream Nitrate loss and Evidence of Saturation Kinetics. Journal of Geophysical Research: Biogeosciences. 114*, G04016, doi:*10.1029/2009JG001017.

Delaware River Basin Commission, 1961. Delaware River Basin Compact. West Trenton, New Jersey. 51 pp.

Delaware River Basin Commission, 2008. Administrative Manual Part III Water Quality Regulations with Amendments through July 16, 2008. 131 pp.

Delaware River Basin Commission, 2010. Delaware River and Bay Integrated List Water Quality Assessment. 46 pp.

Delaware River Fish and Wildlife Management Cooperative, 1982. A Fishery Management Plan for the American Shad (*Alosa Sapidissimia*) in the Delaware River Basin. 26 pp.

Dorfman, R., H. D. Jacoby, and H. A. Thomas, 1972. Models for Managing Regional Water Quality. Harvard University Press. Cambridge, Mass.

Environmental Protection Agency, 1996. Atmospheric Nitrogen Deposition Loadings to the Chesapeake Bay, An Initial Analysis of the Cost-Effectiveness of Control Options. Washington, D.C. 29 pp.

Environmental Protection Agency, 2000. Progress in Water Quality: An Evaluation of the National Investment in Municipal Wastewater Treatment, Chapter 7: Delaware Estuary Case Study. 7.1-7.26.

Environmental Protection Agency, 2000. Ambient Water Quality Criteria Recommendations, Information Supporting the Development of State and Tribal Nutrient Criteria, Rivers and Streams in Nutrient Ecoregion XIV. EPA 822-B-00-02. 20 pp.

Environmental Protection Agency, 2006. Revisions to Total Maximum Daily Loads for Nutrient and Low Dissolved Oxygen under High Flow Conditions Christina River Basin, Pennsylvania, Delaware and Maryland.

Evans, B. M., 2008. An Evaluation of Potential Nitrogen Load Reductions to Long Island Sound from the Connecticut River Basin. Penn State Institutes of Energy and the Environment. University Park, Pennsylvania. 66 pp.

Federal Water Pollution Control Administration, 1966. Delaware Estuary Comprehensive Study, Preliminary Report and Findings. 110 pp.

Gilbert, P. M., C. J. Madden, W. Boynton, D. Flemer, C. Heil, and J. Sharp, 2010. Nutrients in Estuaries: Summary Report of National Estuarine Experts Workgroup 2005-2007. 188 pp.

Interstate Commission on the Delaware River Basin, 1940. The Delaware River Basin Physical Facts. Philadelphia, Pennsylvania.

Johnson, E. L., 1967. A Study in the Economics of Water Quality Management. Water Resources Research. 3(2):291-305.

Jones, C., E. Branosky, M. Selman, and M. Perez, 2010. How Nutrient Trading Could Help Restore the Chesapeake Bay, WRI Working Paper. World Resources Institute. 13 pp.

Kauffman, G., A. Belden, A. Homsey, M. Porter, A. Zarnadze, J. Ehrenfeld, S. Stanwood, L. Sherwin, J. Farrell, D. DeWalle, and C. Cole, 2008. Technical Summary: State of the Delaware Basin Report. University of Delaware, Cornell University, Rutgers University, Pennsylvania State University. 195 pp.

Kauffman, G. J., 2016. Economic Value of Nature and Ecosystems in the Delaware River Basin. Journal of Contemporary Water Research and Education (JCWRE). Universities Council on Water Resources (UCOWR). 158:24-48.

Kauffman, G. J., A. R. Homsey, A. C. Belden, and J. R. Sanchez, 2010. Water Quality Trends in the Delaware River Basin (USA) from 1980 to 2005. Environmental Monitoring and Assessment. 177(1-4):193-225.

Kneese, A. V. and B. T. Bower, 1984. Managing Water Quality: Economics, Technology, Institutions. Resources for the Future. Washington, D.C. 328 pp.

Lyon, R. and S. Farrow, 1995. An Economic Analysis of Clean Water Act Issues. Water Resources Research. 31(1):213-223.

Maass, A., M. Huffschmidt, R. Dorfman, H. Thomas, S. Marglin, and G. Fair, 1962. Design of Water Resources Systems. Harvard University Press. Cambridge, Massachusetts.

Mandarano, L. A., J. P. Featherstone, and K. Paulsen, 2008. Institutions for Interstate Water Resources Management. Journal of the American Water Resources Association. 44(1):136-147.

Moore, R. B., C. M. Johnston, R. A. Smith, and B. Milstead, 2011. Source and Delivery of Nutrients to Receiving Waters in the Northeastern and Mid-Atlantic Regions of the United States. Journal of the American Water Resources Association. 47(5):965-990.

Phillips, S. W. and B. D. Lindsey, 2003. The Influence of Ground Water on Nitrogen Delivery to the Chesapeake Bay. USGS Fact Sheet FS-091-03. 6 pp.

Preston, S.D., R. B. Alexander, G. E. Schwarz, and C. G. Crawford, 2011. Factors Affecting Stream Nutrient Loads: A Synthesis of Regional SPARROW Model Results for the

Continental United States. Journal of the American Water Resources Association. 47(5):891–915.

Rabotyagov, S., T. Campbell, M. Jha, P. W. Gassman, J. Arnold, L. Kurkalova, S. Secchi, H. Feng, and C. L. Kling, 2010. Least-Cost Control of Agricultural Nutrient Contributions to the Gulf of Mexico Hypoxic Zone. Ecological Applications. 20(6):1542-1555.

Reuss, M., 2003. Is it Time to Resurrect the Harvard Water Program? Journal of Water Resources Planning and Management. American Society of Civil Engineers. 357-360.

Roman, C. T., N. Jaworski, F. T. Short, S. Findlay, and R. S. Warren, 2000. Estuaries of the Northeastern United States: Habitat and Land Use Signatures. Estuaries. 23(6):743-764.

Scatena, F. N., D. Curley, S. Laskowski, K. Abbott, H. Bardin, W. Shieh, and J. Johnson, 2006. Water Quality Trading in the Lower Delaware River Basin: A Resource for Practitioners. A Report to the William Penn Foundation by the Institute for Environmental Studies, University of Pennsylvania. 86 pp.

Schaumburg, G. W., 1967. Water Pollution Control in the Delaware Estuary. Harvard Water Program Discussion Paper No. 67-2. Harvard University. 150 pp.

Schleich, J., D. White and K. Stephenson, 1996. Cost Implications in Achieving Alternative Water Quality Targets. Water Resources Research. 32 (9):2879-2884.

Schneider, J., 2007. Development of Numeric Nutrient Criteria for Waters of the State of Delaware and Delaware Bay/Estuary Nutrient DO Concerns. DRBC Joint Monitoring and Water Quality Advisory Committee Meeting.

Scudlark, J. R. and T. M. Church, 1993. Atmospheric Input of Inorganic Nitrogen to Delaware Bay. Estuaries and Coasts. 16(4):747-759.

Secor, D. H. and Gunderson, T. E., 1998. Effects of Hypoxia and Temperature on Survival, Growth, and Respiration of Juvenile Atlantic Sturgeon, *Acipencer Oxyrincus*. Fishery Bulletin. 96:603-613.

Sharp, J. H. and T. M. Church, 1981. Biochemical Modeling in Coastal Waters of the Middle Atlantic States. Limnology and Oceanography. 26(5):843-854.

Sharp, J. H., 2006. How the Delaware Estuary Works. Prepared for Processes Workgroup Meeting. Tiburon, California.

Sharp, J. H., 2010. Estuarine Oxygen Dynamics: What Can We Learn About Hypoxia from Long-Time Records in the Delaware Estuary? Limonology and Oceanography. 55(2):535-548.

Sharp, J. H., C. H. Culberson, and T. M. Church, 1982. The Chemistry of the Delaware Estuary. General Considerations. Limnology and Oceanography. 27(6):1019-1028

Sharp, J. H., J. R. Pennock, T. M. Church, J. M. Tramontano, and L. A. Cifuetes, 1984. The Estuarine Interaction of Nutrients, Organics, and Metals: A Case Study in the Delaware Estuary. The Estuary as a Filter. Academic Press. Inc.

Sharp, J. H., K. Yoshiyama, A. E. Parker, M. C. Schwartz, S. E. Curless, A. Y. Beauregard, J. E. Ossolinski and A. R. Davis, 2009. A Biogeochemical View of Estuarine Eutrophication: Seasonal and Spatial Trends and Correlations in the Delaware Estuary. Estuaries and Coasts. 32(6):1023-1043.

Sharp, J. H., L. A. Cifuentes, R. B. Coffin, and J. R. Pennock, 1986. The Influence of River Variability on the Circulation, Chemistry, and Microbiology of the Delaware Estuary. Estuaries 9(4A):261-269.

Sildorff , E. and T. J. Fikslin, 2010. Continuing Restoration of Dissolved Oxygen in the Delaware Estuary: Historical Data and Current Efforts. 2010 AWRA Conference Philadelphia.

Stoner, N. K., 2011. Memorandum to Regional Administrators Regions 1-10. Working in Partnership with States to Address Phosphorus and Nitrogen Pollution through Use of a Framework for State Nutrient Reductions.

Thoman, R. V., 1972. River Ecology and Man. The Delaware River - A Study in Water Quality Management. R. T. Oglesby, C. A. Carlson, and J. A. McCann, editors. Academic Press Inc. New York. 99-132.

Trench, E. C. T., R. B. Moore, E. A. Ahearn, J. R. Mullaney, R. E. Hickman, and G. E. Schwarz, 2012. Nutrient Concentrations and Loads in the Northeastern United States - Status and Trends, 1975–2003: USGS Scientific Investigations Report 2011–5114. 169 pp.

Trowbridge, P., 2010. Analysis of Nitrogen Loading Reductions for Wastewater Treatment Facilities and Non-Point Sources in the Great Bay Estuary Watershed. New Hampshire Department of Environmental Services. 27 pp.

U.S. Federal Water Pollution Control Administration, 1966. Delaware Estuary Comprehensive Study, Preliminary Report and Findings. 110 pp.

Van Soesbergen, A., R. Brouwer, P. Baan, P. Hellegers, and N. Polman, 2007. Assessing the Cost-Effectiveness of Pollution Abatement Measures in Agriculture, Industry and the Wastewater Treatment Sector. WEMPA Report-07. 31 pp.

Wieland, R., D. Parker, W. Gans, and A. Martin, 2009. Costs and Cost Efficiencies for Some Nutrient Reduction Practices in Maryland. NOAA Chesapeake Bay Office. 58 pp.