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Article

The Cost of Clean Water in the Delaware River Basin (USA)

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Abstract: The Delaware River has made a marked recovery in the half-century since the adoption of the Delaware River Basin Commission (DRBC) Compact in 1961 and passage of the Federal Clean Water Act amendments during the 1970s. During the 1960s, the DRBC set a 3.5 mg/l dissolved oxygen criteria for the river based on an economic analysis that concluded a waste load abatement program designed to meet fishable water quality goals would generate significant recreation and environmental benefits. Scientists with the Delaware Estuary Program have recently called for raising the 1960s DO criteria along the Delaware River from 3.5 mg/l to 5.0 mg/l to protect anadromous American shad and Atlantic sturgeon and address the prospect of rising temperatures, sea levels, and salinity in the estuary. This research concludes through a marginal abatement cost (MAC) analysis that it would be cost effective to raise DO levels to meet a more stringent standard by prioritizing agricultural conservation and wastewater treatment investments in the Delaware River watershed to reduce 90% of the pollutant load 13.6 million kg/year of nitrogen (30 million lb/year) for $160 million at 35% of the $449 million annual cost. The annual least cost to reduce nitrogen loads and raise dissolved oxygen levels to meet more stringent water quality standards in the Delaware River totals $45 million for atmospheric NOX reduction, $130 million for wastewater treatment, $132 million for agriculture conservation, and $141 million for urban stormwater retrofitting. This 21st century least cost analysis estimates that $50 million/year is needed to reduce pollutant loads in the Delaware River to raise dissolved oxygen levels to 4.0 mg/l, $150 million/year is needed to reach 4.5 mg/l, and $449 million/year is needed to reach 5.0 mg/l.

Keywords: watershed; water quality; economics

1. Introduction

Nutrient pollution due to high loads of nitrogen and phosphorus causes costly impacts on the tourism, commercial fishing, recreation, hunting, real estate, and water treatment sectors of the economy [1]. Noting that 50% of the nation's streams have medium to high nutrient levels 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 [2].

Nutrient load reduction costs in the nation's waters are significant and range from $35 million/year in the 16,500 km^2 Wisconsin Fox-Wolf River watershed [3] to $203 million/year in the 26,200 km^2 Connecticut River/Long Island Sound Basin [4]. The Chesapeake Bay Program [5] estimated restoration of the 166,000 km^2 Chesapeake Bay watershed could cost $1 billion/year. Rabotyagov et al. [6] estimated a cost of $1.8 billion/year to reduce nutrient loads and increase dissolved oxygen levels in the 492,000 km^2 Upper Mississippi River Basin. Lyon and Farrow [7] reported to EPA that Federal Clean Water Act stormwater programs could cost up to $14 billion/year nationwide.

The Interstate Commission on the Delaware River Basin [8] 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

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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 [9]. For over a half century, the DRBC has been empowered by this compulsory 1961 Federal/state compact to oversee water pollution control programs on the Delaware River [10].

The Delaware River has a long history of nutrient pollution [11, 12, 13, 14, 15, and 16] but the estuary has recovered considerably in the last several decades due to restoration efforts by DRBC, EPA, and the states [17, 18, and 19]. A century-long water quality record reconstructed by Sharp {20] indicates the tidal Delaware has made one of the most extensive recoveries of any estuary in the world as dissolved oxygen levels declined to zero during the 1950s and 1960s and increased to near 400 *u*mol/L by the turn of the 21st century (Figure 1).

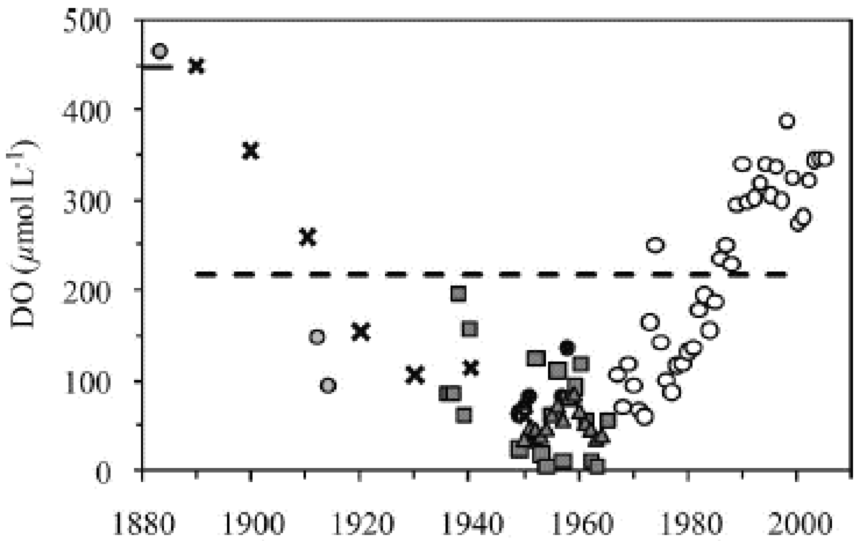

Figure 1. Dissolved oxygen (July-August) in the Delaware River near Philadelphia, 1880-present (Sharp 2010). Data from 1967–present (open circles), 1949-1952 and 1957-1959 (solid circles), 1950-1964 (solid triangles), 1936-1965 (solid squares), 1983, 1912,1914 (solid circles).

While water quality has measurably improved in the Delaware Estuary since the adoption of the 1961 DRBC Compact, dissolved oxygen levels still do not fully meet the criteria of 3.5 mg/l during the summer when DO saturation declines with warming water temperatures. Scientists with the Delaware Estuary Program and the DRBC have discussed setting more rigorous DO criteria along the tidal Delaware River (to at least 5.0 mg/l) to protect year-round propagation of anadromous fish such as the American shad and Atlantic sturgeon [21, 22}. 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.

2. Research Objectives

While dissolved oxygen levels have recovered over the last half century, little is known about modern costs to restore the Delaware River to meet fishable water quality standards. The objectives of this research are to estimate the costs of investments to reduce pollutant loads and restore the Delaware River to meet more protective year-round fishable dissolved oxygen criteria in accordance with DRBC, EPA, and state water quality standards.

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3. The Delaware River

While just the 33rd largest river in the United States, 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 State 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 part of Maryland.

The Delaware Basin covers just 0.4% of the continental U.S. yet supplies drinking water to 5% of the nation's population and the first (New York City) and seventh (Philadelphia) largest metropolitan economies in the nation [23]. 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. Between 2000 and 2010, the population in the Delaware Basin increased by a half million people (Figure 3), a figure equal to the combined population of the cities of Camden, Trenton, and Wilmington.

The Delaware Estuary extends 130 mi (208 km) from the Atlantic Ocean to the head of tide at Trenton [24]. High nutrient loads discharged from tributaries near Philadelphia and rural streams along the bay are diluted by saltwater as the estuary widens toward the mouth of the bay [13]. The Delaware Estuary recirculates every 8 days (Table 1) with half mixing with freshwater from the Delaware River at Trenton, Schuylkill, Lehigh, Brandywine, and smaller tributaries and the other half from the Atlantic Ocean [17]. The estuary is relatively turbid with a light extinction coefficient of 0.3-7.0 [25].

The DRBC [26, 27] classifies the Delaware River and Bay according to 10 non-tidal and tidal water quality management zones based on: (a) Agricultural, Industrial, and Public Water Supply, (b) Wildlife, Fish and Aquatic Life, (c) Recreation (Swimming, Boating, Fishing, Wading, (d) Navigation, and (e) Waste Assimilation designated uses (Figure 4). In the tidal Delaware, summer DO criteria varies from 3.5 mg/l in Zones 3 and 4 from Rancocas Creek past Philadelphia to Wilmington and 4.5 mg/l in Zone 5 from Wilmington to the C&D Canal. Minimum DO criteria is 6.5 mg/l during spring and fall in Zones 2 through 5 to allow for seasonal spawning and propagation of resident and anadromous fish.

Despite high nutrient loading, the Delaware Estuary does not exhibit classic eutrophication symptoms of hypoxia or algal blooms as observed in the nearby Chesapeake Bay. Algal blooms are inhibited by the assimilative capacity of wetlands that rim the Delaware Bay and by low light levels in the well-flushed and turbid Delaware Estuary. Through the wide 17 mi (27 km) mouth of Delaware Bay, the Atlantic Ocean contributes significant tidal flushing, thus limiting algal blooms that cause fish kills except during an occasional spring bloom in the mid estuary [17].

Table 1. 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

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Figure. 2. The Delaware River Basin (DRBC 2010)

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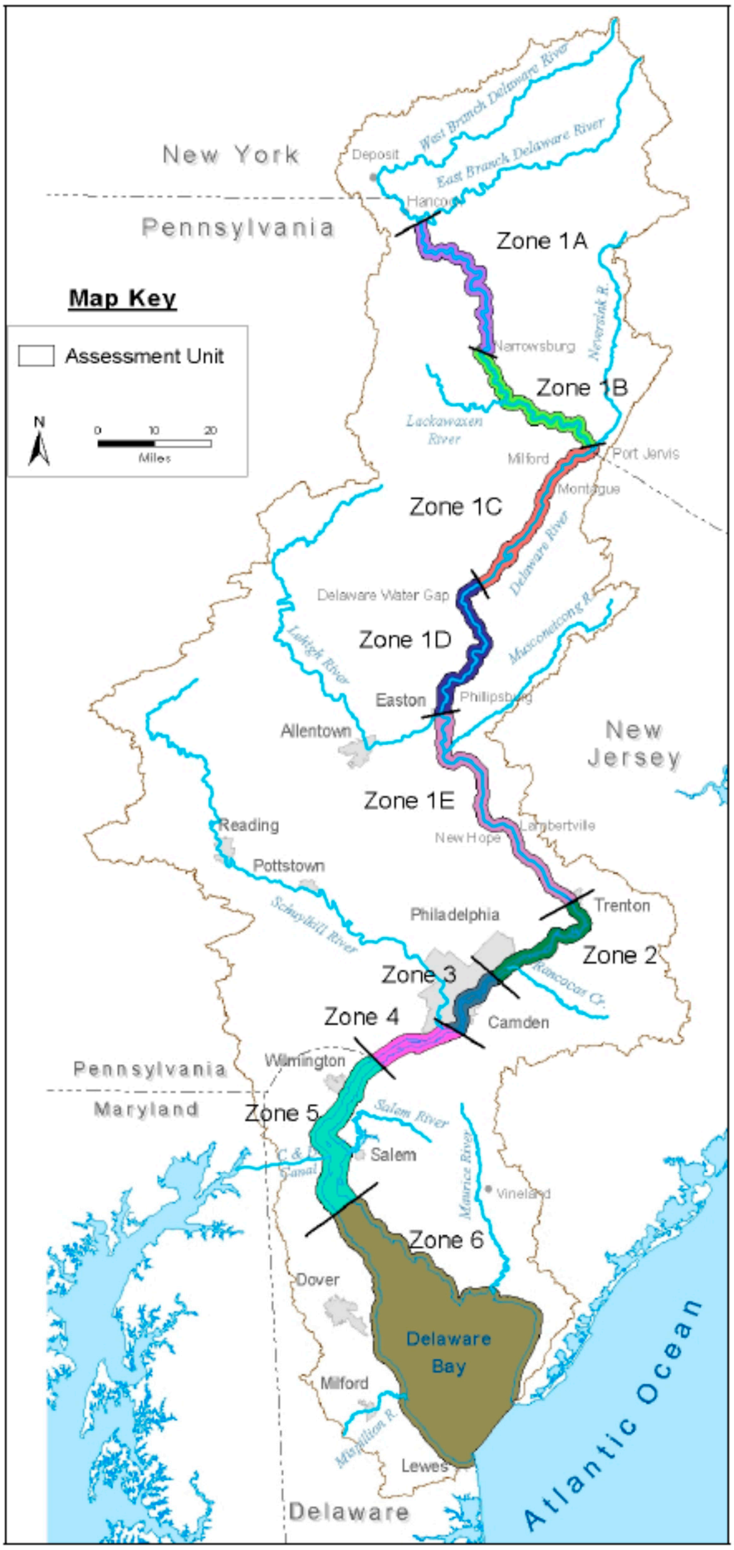

Figure. 3. Delaware River water quality management zones (DRBC 2010)

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During the 1960s when the river was anoxic and a decade before the 1970s Federal Clean Water Act Amendments, the DRBC imposed waste load allocations on 80 dischargers and adopted the first interstate water quality standards along the Delaware River. The Federal Water Pollution Control Administration (FWPCA) and Harvard Water Program [28, 29, 30, and 31] issued an economic report in 1966 that concluded water supply and recreation benefits due to improved water quality in the Delaware River would exceed water pollution control costs [32, 33, and 34].

The 1966 FWPCA study estimated pollutant reduction costs 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 2). Thomann [32] estimated shad passage would achieve 80% survival if DO improved from 0.5 mg/l in 1964 to a future level of 3.0 mg/l. In 1967, the DRBC considered this economic 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. In 1968, the DRBC quite presciently anticipated that the waste load abatement plan would remove 85% to 90% of carbonaceous BOD and boost DO from near zero to 4.0 mg/l at Philadelphia (Figure 4).

Table 2. Costs to meet water quality objectives in the Delaware Estuary [28]

Objective Set	**DO Criteria (mg/l)**	**BOD/COD Residual**		**% Pollution Removal**	**Total Costs ($1964) ($M/yr)**	**Marginal Costs ($1964) ($M/yr)**	**% Survival Shad Passage**
		(lb/day)	**(kg/day)**				
I.	4.5	100,000	45,360	92%-98%	490	160-260	
II.	4.0	200,000	90,720	90%	230-330	100-150	90%
III.	3.0	500,000	226,800	75%	130-180	30-30	80%
IV.	2.5	800,000	362,880	50%	100-150	70-120	
V.	0.5	status quo			30	0	20%

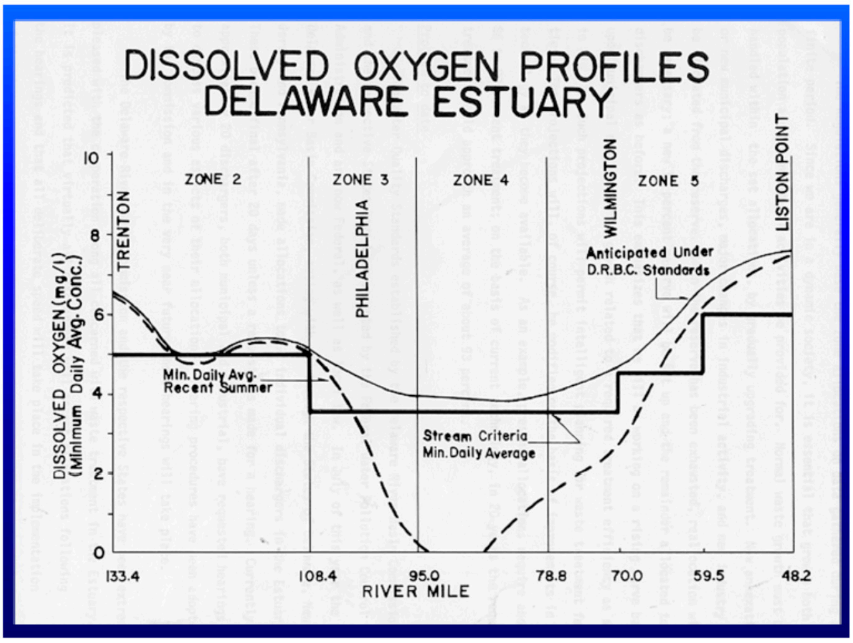

Figure. 4. DRBC dissolved oxygen criteria along the Delaware Estuary in 1968.

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Dissolved oxygen levels in the Delaware Estuary vary by water temperature, sunlight, winds, and pollutant loads [1]. By 2010, DO levels in the Delaware River at Ben Franklin Bridge at Philadelphia mostly exceeded the criteria except for violations below 3.5 mg/l during the hot summer months of June through August (Figure 5). During warm summers, 0.5% of readings since 2000 did not meet the 3.5 mg/l criteria. In July and August, DO in the Delaware River at Philadelphia occasionally declined below the 3.5 mg/l criteria (46% DO saturation) when water temperatures approach 30° C or 86° F (Figure 6). At 30°C, DO is 100% saturated at 7.54 mg/l and 80% saturated at 6 mg/l, therefore, when water temperatures rise to 30°C, a future DRBC DO standard higher than 5 mg/l (66% saturation) may prove difficult to achieve given the warm water temperatures that occur during summer.

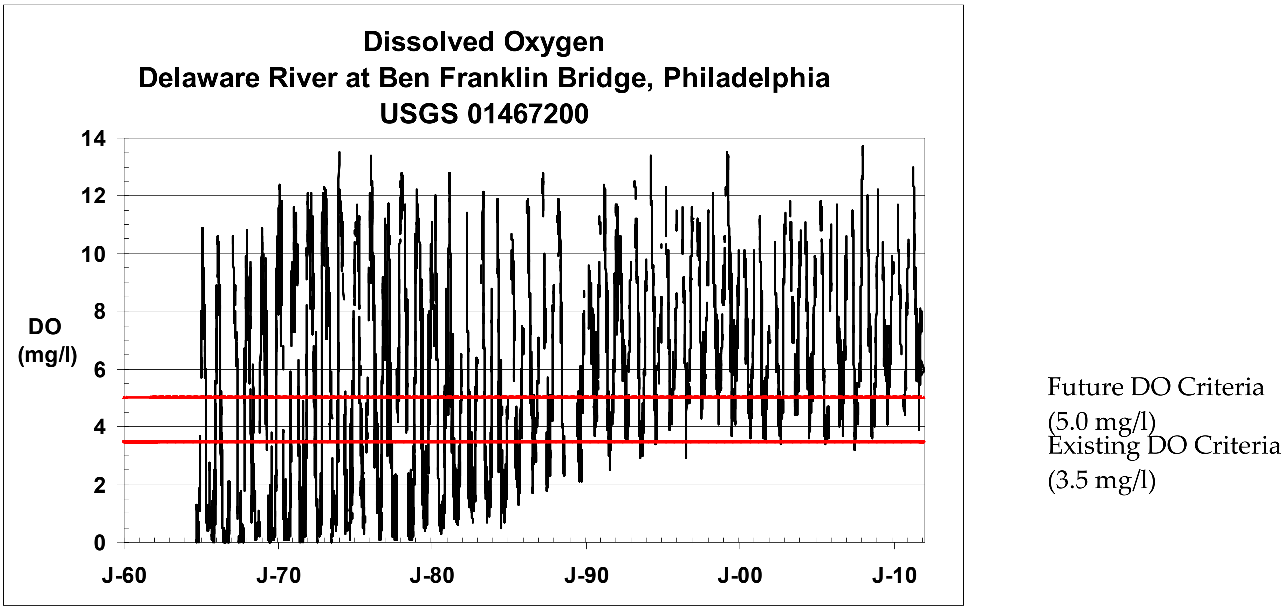

Figure. 5. Mean Daily Dissolved Oxygen at Ben Franklin Bridge along Delaware River

Scientists on the Delaware Estuary Program Science and Technical Advisory Committee have recommended that the DRBC raise the fishable DO standard from the current level of 3.5 mg/l to at least 5.0 mg/l in Zones 3 and 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 [35, 36]. Secor and Gunderson [37] found that juvenile Atlantic sturgeon may suffer over 50% mortality at 25° C (77° F) when DO is 3.5 mg/l. Juvenile shortnose sturgeon are prone to 50% mortality when DO declines below 3.0 mg/l at 25° C [38]. In 2017, the DRBC began reviewing water quality regulations to determine whether DO criteria should be increased from the current 3.5 mg/l to a higher level to provide more protection of anadromous fish spawning and year-round propagation of the fishery.

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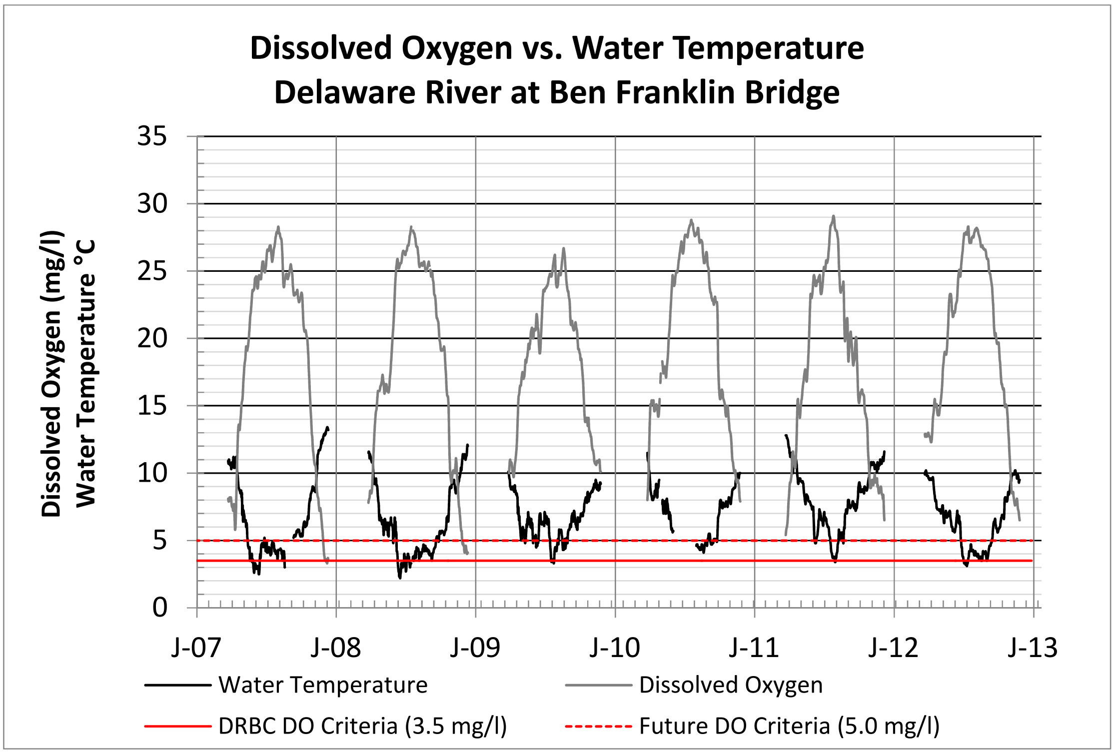

Figure. 6. Water temperature/dissolved oxygen along the Delaware River (www.usgs.gov)

4. Methods

With the following research we estimate the modern 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 mg/l) in the Delaware River. To estimate the most cost-effective combination of nitrogen load reductions, we (1) quantified nitrogen loads in the Delaware Basin from atmospheric, urban/suburban, wastewater, and agricultural sources and estimated pollutant load reductions needed to improve dissolved oxygen in the Delaware River from current 3.5 mg/l to future more protective standard, (2) estimated costs of nitrogen load reductions to improve dissolved oxygen levels in the tidal Delaware River for various best management practice scenarios, and (3) constructed marginal abatement cost curves to define annual least costs to raise dissolved oxygen levels to more stringent fishable criteria.

Nitrogen Loads: We estimated annual nitrogen loads in the Delaware Basin in Delaware, New Jersey, New York, and Pennsylvania using the USGS SPAtially Referenced Regressions on Watershed (SPARROW) model [39]. The Delaware River receives the second highest nitrogen load of any river basin along the Atlantic Coast of the USA (Table 3). We utilized the SPARROW model that estimates nitrogen 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 [40]. The USGS SPARROW model calibrates nitrogen load estimates with EPA STORET water quality monitoring data the model is 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 3. SPARROW nitrogen loads in Atlantic Coast river basins (Moore et al. 2011)

River Basin	Drainage Area (km^2)	Nitrogen Load (kg/yr)	Unit N Load ($kg/km^2/yr$)
Susquehanna	71,199	66,320,320	931
Delaware	30,611	45,876,700	1,499
Potomac	37,964	40,593,956	1,069
Hudson	34,610	26,069,588	753
James	26,778	15,873,656	593
Connecticut	29,166	15,650,288	537

The USGS SPARROW model simulates nitrogen removal based on hydrological processes such as denitrification, particulate settling, and water velocity [41]. Based on the delivery fraction of nitrogen (proportion of N load delivered to the outlet), BMPs implemented in watersheds closest to the Delaware Estuary provide the most immediate improvements in water quality (Figure 7). Conversely, nitrogen yields from watersheds far from the estuary (headwaters of the upper Schuylkill) are less likely to influence water quality in the Delaware Estuary.

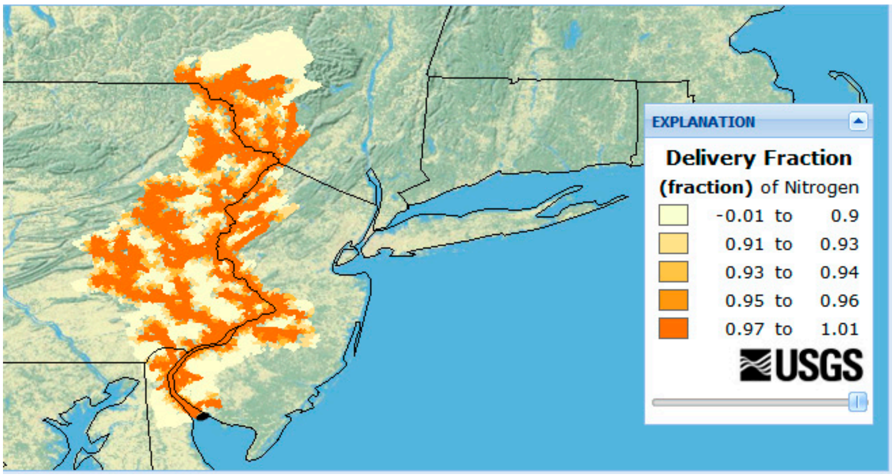

Figure. 7. Delivery fraction of nitrogen in the Delaware Basin (USGS SPARROW 2016)

Nitrogen Load Reduction Costs: We estimated N load reductions needed to improve water quality to meet a future 5.0 mg/l DO standard in the Delaware River between Philadelphia and Wilmington. We examined the EPA Water Quality Analysis Simulation Program (WASP), USGS Hydrological Simulation Program-Fortran (HSPF), and Generalized Watershed Loading Function (GWLF) to estimate TMDL pollutant load reductions in the lower Delaware Basin (EPA 2000). These hydrodynamic models suggest "better-than-secondary" treatment is needed to meet a more stringent DO water quality standard of 5 mg/l in the Delaware River at Philadelphia.

We reviewed a survey of 15 TMDL models by Scatena et al. [42] in the lower Delaware River that suggests 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 8). Similarly, the Brandywine-Christina watershed TMDL model estimated a 38% reduction in nitrogen loads is needed to meet dissolved oxygen water quality criteria of 5 mg/l in the watershed that contributes 8% of the N load to the Delaware Estuary [43].

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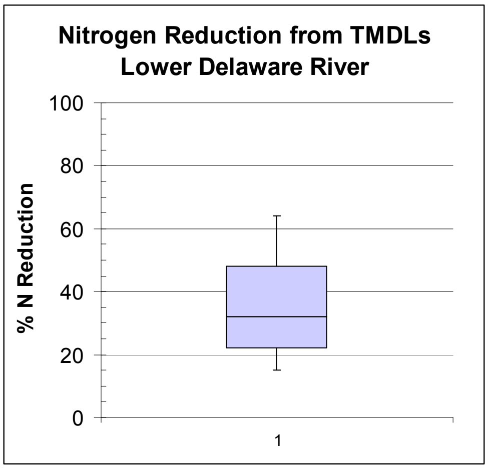

Figure. 8. Nitrogen load reductions from TMDL models for the lower Delaware River (Scatena et al. 2006)

BMP Installation Costs: We derived unit costs of N load reductions ($/lb N reduced) for point source wastewater treatment BMPs and nonpoint source BMPs such as atmospheric controls (vehicle exhaust and industrial plant scrubbers), urban stormwater retrofitting, stream restoration, wetlands, and agricultural practices such as no till, cover crops, forest buffers, and animal waste management (Table 4).

Table 4. Nitrogen reduction best management practices

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

Our research reveals that nitrogen reduction costs vary from $2.64-24.20/kg N ($1.20-$11.0 $/lb N) for agricultural conservation, $18.83-$174/kg N ($8.56- $79.00 $/lb N) for wastewater treatment, $165-$639/kg N ($75.00-$132.00 $/lb N) for airborne emissions controls, and $198-$1,100/kg N ($90.00-$500.00 $/lb N) for urban/suburban stormwater retrofit BMPs (Table 5). Wastewater treatment N load reduction costs vary from $18.83-$60.83/kg N ($8.56-$27.65 $/lb N) in the Chesapeake Bay watershed [5] to $38.06/kg N ($17.30 $/lb N) in the Connecticut River Basin [4] and $139.00-$174.00/kg N ($63.00-$79.00 $/lb N) in Maine and

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New Hampshire [5, 44, 45]. Airborne deposition nitrogen load reduction costs in the Chesapeake Bay range from $165/kg N ($75.00/lb N) for Clean Air Act programs [44] to $639/kg N ($132.00/lb N) for low emission vehicle programs {43, 44, 48]. Urban stormwater retrofitting is a more expensive option with costs that range from $198-$1,100/kg N ($90 to $500/lb N) reduced [5, 44, 46, 47].

Our survey of the literature indicates that agricultural conservation practices reduce N loads by 40% for grass buffers to 90% for cover crops at unit costs that range from $2.64/kg N ($1.20/lb N) for forest buffers to $22.24/kg N ($10.11/lb N) for cover crops [4, 44, 46, 47]. Agricultural nutrient management plans reduce N by 20% at a cost of $4.41 $/lb N. No-till cropping can reduce N by 55% at a cost of $7.04/kg N) ($3.20/lb N) reduced. Forest buffers remove 50% of N at $2.64 to $14.94/kg N ($1.20 to $6.79 $/lb N). Grass buffers remove 40% of N at $3.45 to $14.87/kg N ($1.57 to 6.76 $/lb N).

Table 5. Nitrogen reduction costs by source

Location	Source	Atmospheric Deposition		Wastewater Treatment		Urban/Sub. Stormwater		Agriculture Conservation	
		($/lb N)	($/kg N)	($/lb N)	($/kg N)	($/lb N)	($/kg N)	($/lb N)	($/kg N)
Chesapeake Bay	[44] Jones et al. 2010	75	165	27.65	60.83	200-500	440-1,100	1.20-4.70	2.64-10.34
New Hampshire	[45] Trowbridge 2010			63-79	139-174				
Connecticut R.	[4] Evans 2008			17.30	38.06	137	301	4.93	10.85
Iowa	USDA NRCS					90	198	2.00-11.00	4.40-24.20
Chesapeake Bay	[5] Chesapeake Bay 2004			8.56	18.83	>100	>220	1.57-4.41	3.45-9.70
United States	[48] EPA 1996	75-132	165-639						
Maryland	[47] Weiland 2009					104-210	229-462	1.57-10.11	3.45-22.24

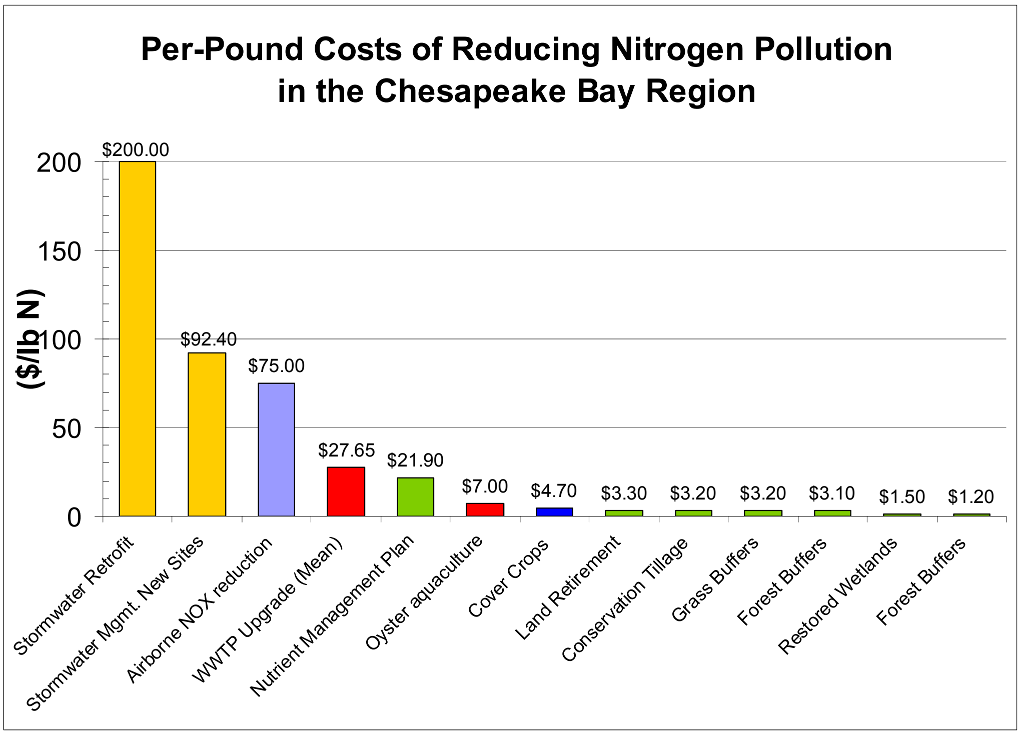

Figure. 9. Costs ($2010) to reduce nitrogen pollution in the Chesapeake Bay region (Jones et al. 2010, Chesapeake Bay Program and World Resources Institute)

We calculated costs to reduce nitrogen loads by 20% (25th percentile) 32% (median), and 48% (75th percentile) to meet a more stringent DRBC dissolved oxygen standard by multiplying N load reduction rates (kg/year) by the unit cost ($/kg) in $2010 for atmospheric NOX reduction $165/kg ($75.00/lb), wastewater treatment $61.60/kg ($28.00/lb), agriculture conservation $11.00/kg ($5.00/lb), and urban/suburban $440/kg ($200/lb) BMPs (Figure 9). Using benefits (value) transfer principles, we translated nitrogen load reduction costs from nearby watersheds (such as the Chesapeake Bay) to the Delaware River watershed since the adjacent watersheds share similar climate, soils, topography, physiography, and hydrogeology.

Total Nitrogen Load Reduction Costs: We estimated costs to reduce nitrogen loads by median 32% by maximizing load reductions from least cost agriculture and wastewater sources for the following 5 options. Option 1 would reduce nitrogen loads equally by median 32% from all sources (agriculture, wastewater, atmospheric, and urban/suburban stormwater. Option 2 would reduce nitrogen loads from agriculture by 32%, wastewater by 47%, atmospheric deposition by 5%, and urban/suburban stormwater by 5%. Option 3 would reduce nitrogen loads from agriculture by 60%, wastewater by 29%, atmospheric deposition by 5%, and urban/suburban stormwater by 5%. Option 4 would reduce nitrogen loads from agriculture by 75%, wastewater by 20%, atmospheric deposition by 5%, and urban/suburban stormwater by 5%. Options 5 would reduce nitrogen loads from agriculture by 90%, wastewater by 10%, atmospheric deposition by 5%, and urban/suburban stormwater by 5%.

Marginal Abatement Costs: We constructed nitrogen marginal abatement cost (MAC) curves to determine cost effective N load reductions to improve water quality by raising dissolved oxygen 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. The MAC curve is constructed by plotting pollutant load reductions by percentage or in kg/year (lb/year) for the practices and by the annual costs of these measures. The MAC curves are constructed by plotting N load reduction costs ($/year) on the horizontal axis and 25th, 50th (median), and 75th percentile N load reductions on the vertical axis. MAC curves [49] depict relatively inexpensive measures on the left and more expensive measures to the right (Figure 10).

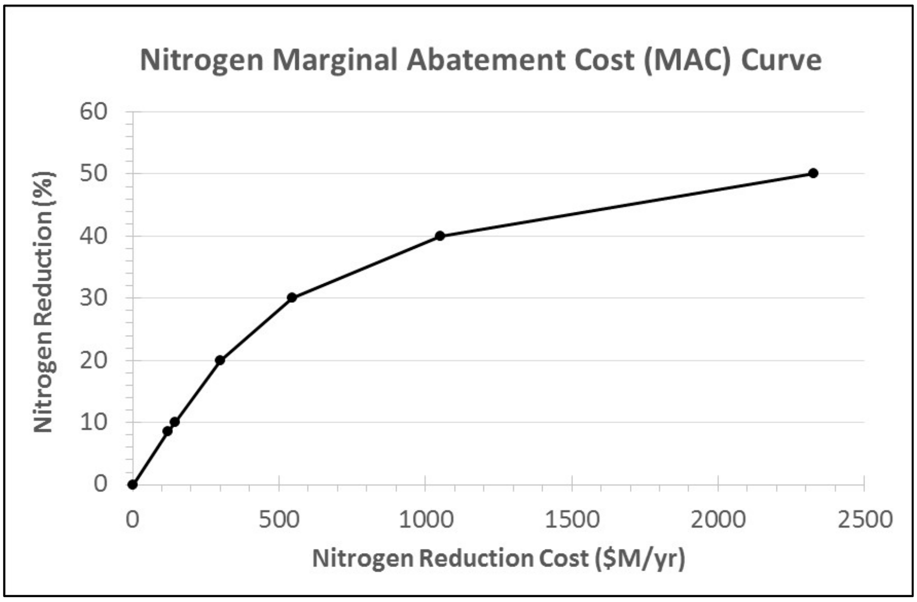

Figure 10. Nitrogen marginal abatement cost (MAC) curve in the Netherlands (Van Soesbergen et al. 2007)

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5. Results

We utilized the USGS SPARROW model that indicates the highest nitrogen loads in the Delaware River watershed are delivered in the Schuylkill River and Brandywine Christina watersheds in southeastern Pennsylvania (Figure 11). The SPARROW model utilizes land cover data to predict nitrogen loads from urban/suburban and agricultural runoff. In 2006, our GIS analysis indicates the Delaware Basin was covered by 63% forest/wetlands, 20% agriculture, and 17% urban/suburban land (Figure 12). Pennsylvania covers 51%, New Jersey and New York each cover 21%, and Delaware covers 8% of the Delaware River Basin. The spatial distribution and fragmentation of land cover types affect pollutant loads to waterways, for example, farmed areas next to streams will deliver higher nitrogen yield that can be filtered by riparian forested buffer areas.

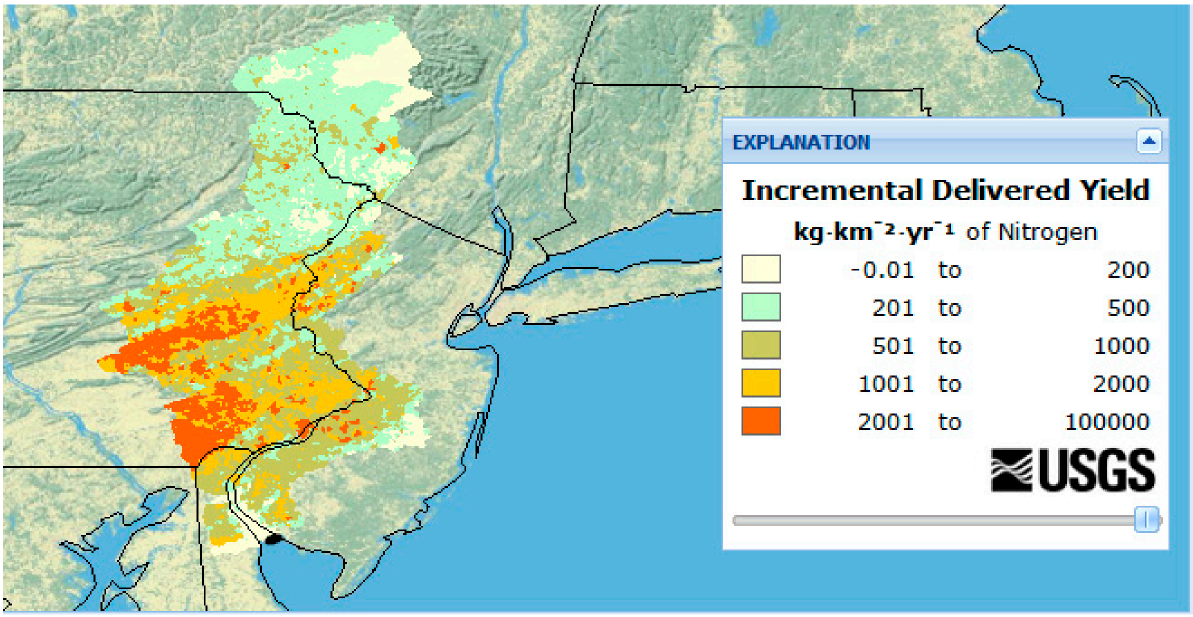

Figure. 11. Incremental delivered nitrogen yield to Delaware Basin from SPARROW model

In the Delaware Basin, our analysis using the SPARROW model indicates almost half (46%) of the nitrogen flows from wastewater discharges and a third (29%) emanates from agriculture fertilizer/manure runoff (Figure 13). 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 14). New York and Delaware contribute 4% and 3% of the nitrogen.

From the USGS SPARROW model, we found three watersheds – the Delaware River at Trenton, Schuylkill River, and above Philadelphia tributaries - deliver 80% of the nitrogen load to the estuary (Figure 15). 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

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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%).

We observed that N loads at USGS gages compare within 25% to 30% of modeled loads from SPARROW [50]. The observed annual N load at Delaware River at Trenton is 14.2 million kg (31.2 million lb) compared to 11.4 million kg (25.1 million lb) from SPARROW. Along the Schuylkill, the observed annual N load is 9.4 million kg (20.8 million lb) versus 13.1 million kg (28.9 million lb) from the SPARROW model.

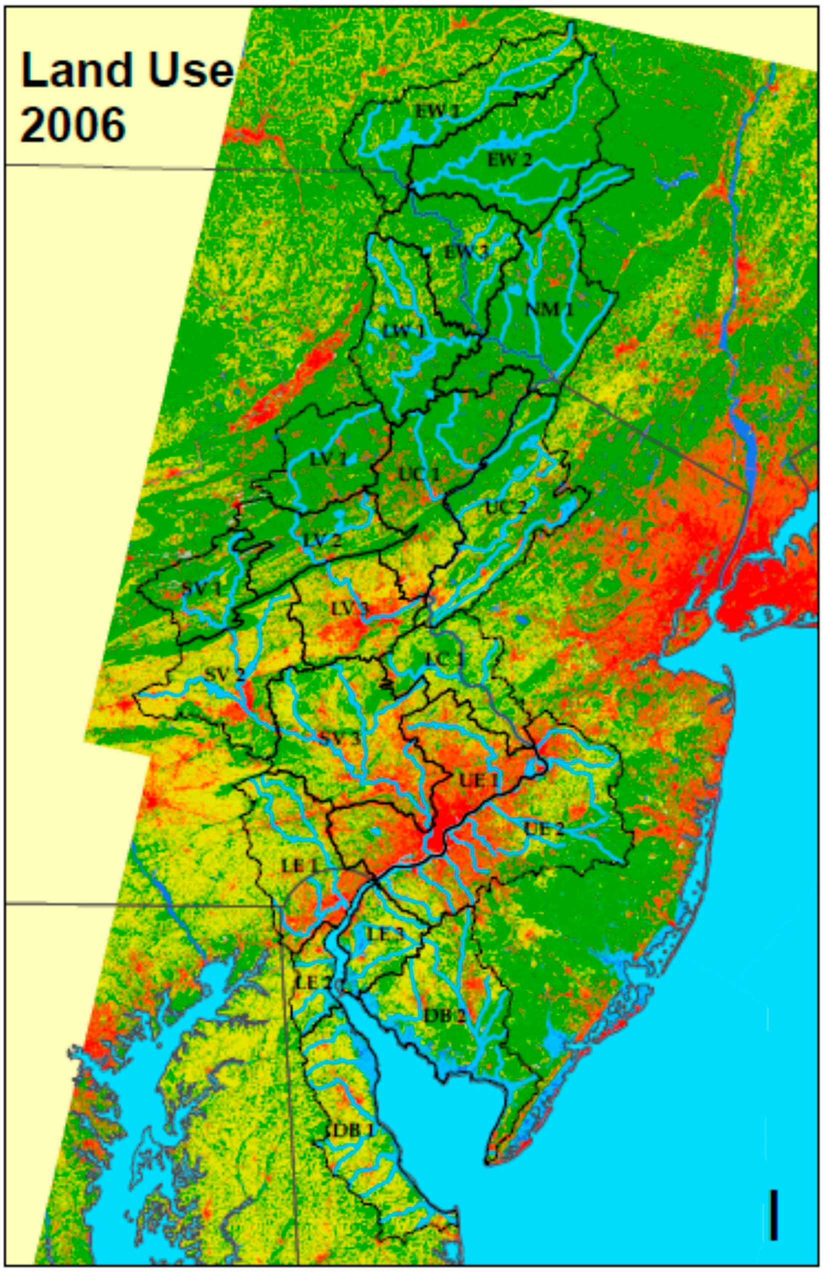

Figure 12. Land cover in the Delaware River Basin, 2006 (NOAA CSC).
Land uses are forest (green), wetlands/water (blue), urban/suburban (red), agriculture (yellow)

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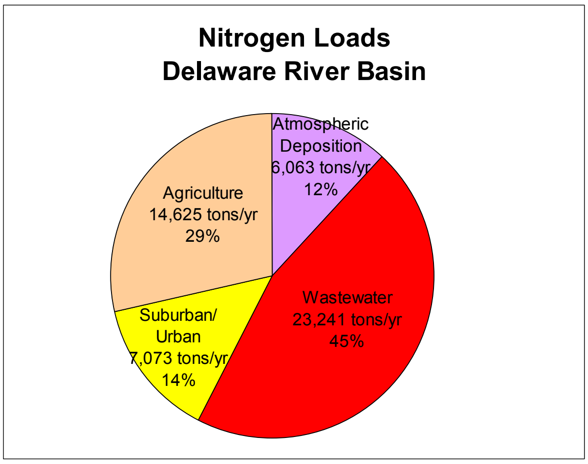

Figure. 13. Annual nitrogen loads by source in the Delaware Basin (Moore et al. 2011)

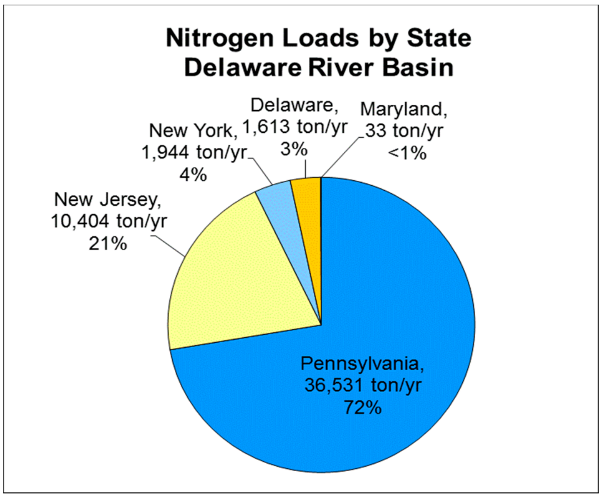

Figure. 14. Annual nitrogen loads by state in the Delaware Basin (Moore et al. 2011)

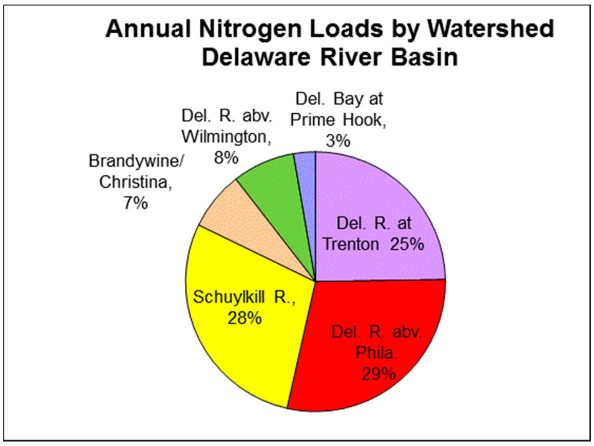

Figure. 15. Annual nitrogen loads by watershed in the Delaware Basin (Moore et al. 2011)

Under Option 1, we estimate that nitrogen loads must be reduced by 14.7 million kg/year (32.3 million lb/year) to achieve 32 % reductions applied equally to all sources (Table 6). Under this uniform load

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reduction scenario, wastewater N loads are reduced by 6.8 million kg/year (14.9 million lb/year) followed by agriculture by 4.3 million kg/year (9.4 million lb/yr), urban/suburban by 2.0 million kg/year (4.5 million lb/year), and atmospheric reduction by 1.8 million kg/year (3.9 million lb/year)). The cost to reduce N loads evenly by 32% for each source is $1.66 billion/year with the largest costs borne by urban/suburban stormwater retrofitting ($905 million/year) with the highest unit cost followed by wastewater discharge ($416 million/year), atmospheric NOX reduction ($291 million/year), and agriculture conservation ($47 million) with the lowest unit cost.

According to Option 1, to reduce N equally by 32% from all sources, we estimate that annual loads must be reduced by 10.6 million kg in Pennsylvania for $1.2 billion, 3.0 million kg in New Jersey for $317 million, 600,000 kg in New York for $95 million, 500,000 kg in Delaware for $60 million, and 11,000 kg in Maryland for $700,000.

Our review of 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 16), 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%).

We found that the least cost (Option 5) would reduce N loads by median 32% or 14.5 million kg/yr (32 million lb/year) 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.

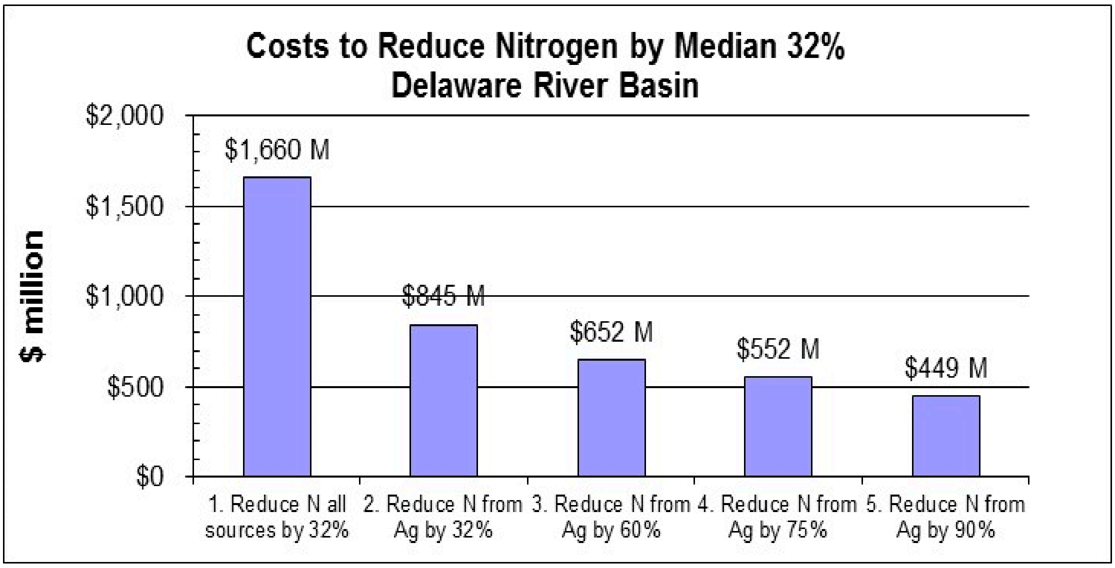

Figure 16. Costs ($2010) to reduce nitrogen loads by 32% in the Delaware Basin

According to Option 5, we conclude that 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 17). Covering half of the Basin, Pennsylvania's annual share is $322 million or 72% of the N load reduction cost (Figure 18). New Jersey would bear $87 million or 19% of the cost. New York State

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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.

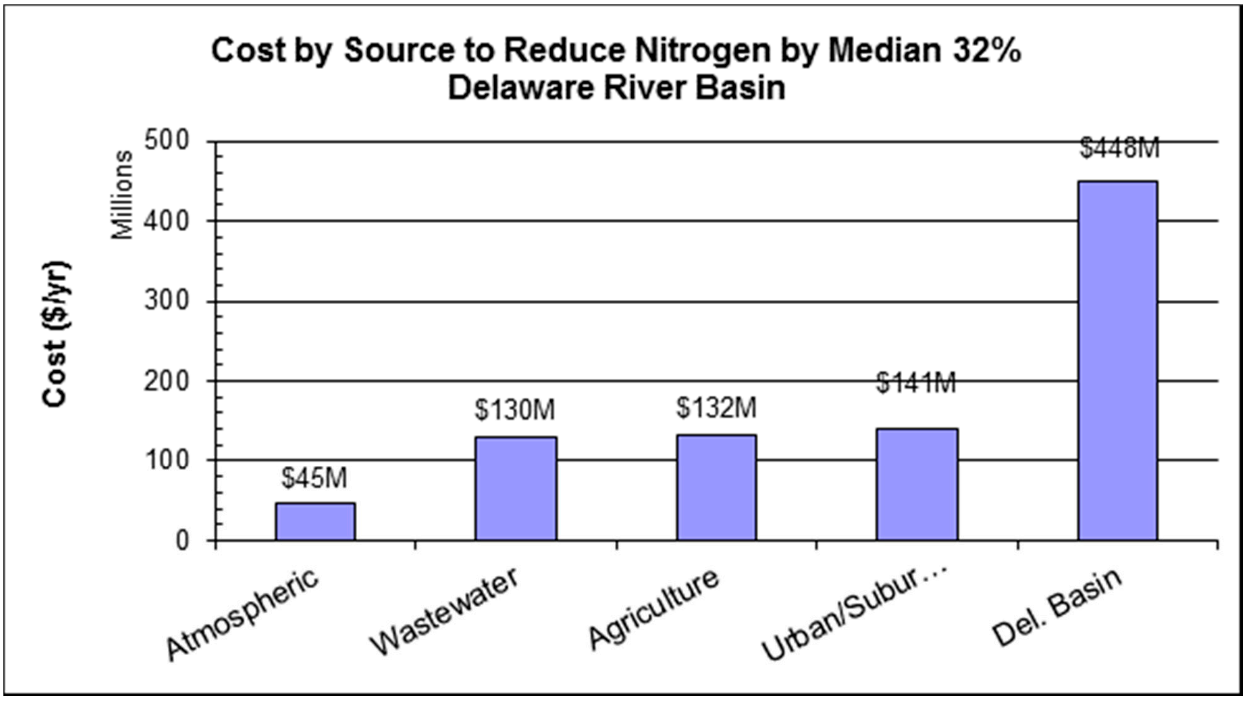

Figure 17. Least cost ($2010) by source to reduce nitrogen loads by 32% in Delaware Basin

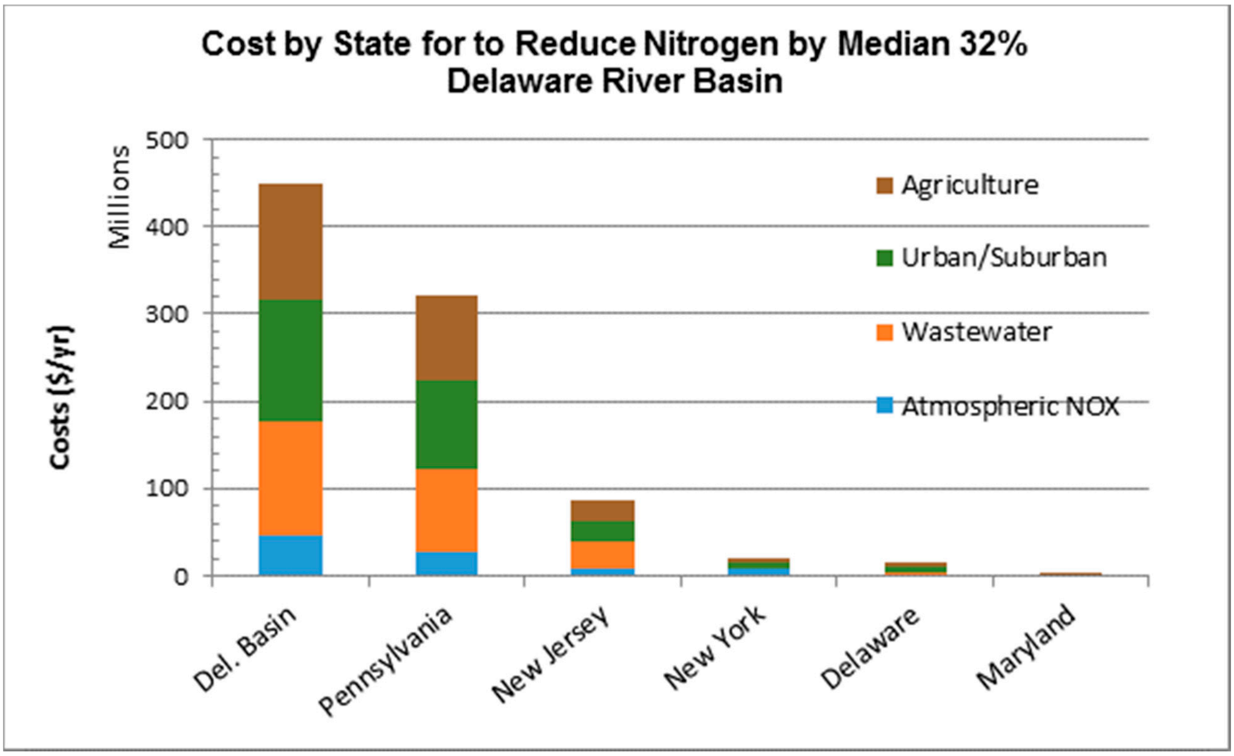

Figure 18. Least cost ($2010) by state to reduce nitrogen loads by 32% in Delaware Basin

Table 6. Least Cost ($2010) by state to reduce nitrogen by median 32% in Delaware Basin

State	Drainage Area (km²)	Pop. (2010)	Nitrogen Reduction (32%) (M kg/yr)	Atmospheric Deposition (5%) (M kg/yr)	Wastewater Discharge (10%) (M kg/yr)	Urban/ Suburban (5%) (M kg/yr)	Agriculture Conservation (90%) (M kg/yr)
Pennsylvania	15,506	5,478,577	10.91	0.18	1.55	0.23	8.95
New Jersey	6,374	1,945,966	2.73	0.05	0.50	0.05	2.14
New York	6,358	121,160	0.45	0.05	0.01	0.01	0.36
Delaware	2,352	703,963	0.55	0.00	0.05	0.01	0.45
Maryland	21	6,339	0.02	0.00	0.00	0.00	0.00
Del. Basin	30,611	**8,256,005**	14.68	0.27	2.09	0.32	12.00
State	**Drainage Area (km²)**	**Pop. (2010)**	**Nitrogen Reduction Cost ($M/yr)**	**Atmospheric Deposition ($165/kg N) ($M/yr)**	**Wastewater Discharge ($62/kg N) ($M/yr)**	**Urban/ Suburban ($440/kg N) ($M/yr)**	**Agriculture Conservation ($11/kg N) ($M/yr)**
Pennsylvania	15,506	5,478,577	322	27	94	102	99
New Jersey	6,374	1,945,966	87	8	31	25	23
New York	6,358	121,160	19	8	0.6	6	4
Delaware	2,352	703,963	16	1	3	6	5
Maryland	21	6,339	0.3	0.02	0	0.08	0.2
Del. Basin	30,611	**8,256,005**	**449**	**45**	**130**	**142**	**132**
State	**Drainage Area (km²)**	**Pop. (2010)**	**Nitrogen Reduction Cost ($/capita/yr)**	**Atmospheric Deposition ($165/kg N) ($/capita/yr)**	**Wastewater Discharge ($62/kg N) ($/capita/yr)**	**Urban/ Suburban ($440/kg N) ($/capita/yr)**	**Agriculture Conservation ($11/kg N) ($/capita/yr)**
Pennsylvania	15,506	5,478,577	59	5	17	19	18
New Jersey	6,374	1,945,966	45	4	16	13	12
New York	6,358	121,160	157	66	5	50	33
Delaware	2,352	703,963	23	1	4	9	7
Maryland	21	6,339	47	3	0	13	32
Del. Basin	30,611	**8,256,005**	**54**	**5**	**16**	**17**	**16**

On a watershed basis, we estimate that 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 19 and Table 7). 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.

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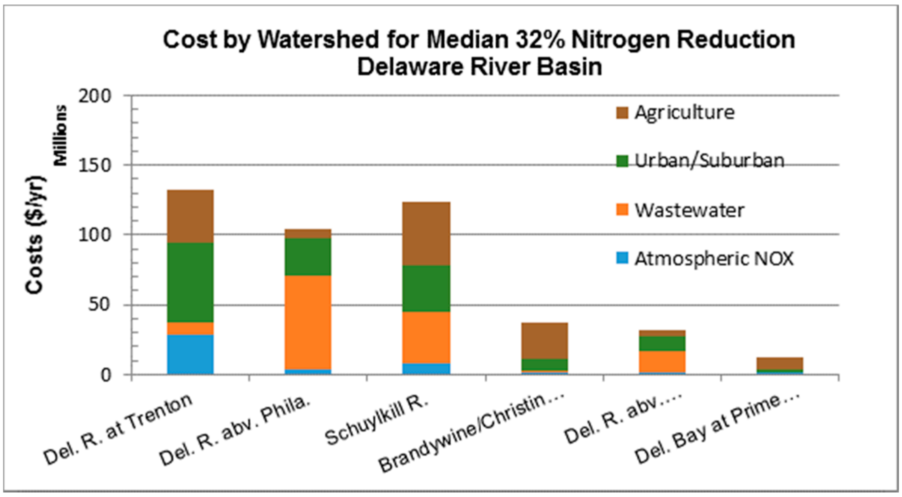

Figure 19. Least cost by watershed to reduce nitrogen loads by 32% in the Delaware Basin

Table 7. Least cost by watershed to reduce nitrogen by median 32% in the Delaware Basin

Watershed	**Drainage Area (mi^2)**	**Nitrogen Reduction (32%) (M kg/yr)**	**Atmospheric Deposition (5%) (M kg/yr)**	**Wastewater Discharge (10%) (M kg/yr)**	**Urban/ Suburban (5%) (M kg/yr)**	**Agriculture Conservation (90%) (M kg/yr)**
Del. R. at Trenton	17,731	3.91	0.18	0.15	0.14	3.45
Del. R. above Phila.	3,227	1.82	0.02	1.09	0.05	0.64
Schuylkill R.	4,905	4.91	0.05	0.59	0.09	4.18
Brandywine/Christina	1,453	2.36	0.01	0.01	0.02	2.32
Del. R. above Wilmington	1,264	0.68	0.01	0.23	0.03	0.41
Del. Bay at Prime Hook	1,896	0.82	0.01	0.01	0.00	0.82
Delaware Basin	30,477	14.55	0.27	2.09	0.32	11.86
Watershed	**Drainage Area (mi^2)**	**Nitrogen Reduction ($M/yr)**	**Atmospheric ($165/kg N) ($M/yr)**	**Wastewater ($62/kg N) ($M/yr)**	**Urban/Sub. ($440/kg N) ($M/yr)**	**Agriculture ($11/kg N) ($M/yr)**
Del. R. at Trenton	17,731	132	28	9	57	38
Del. R. above. Phila.	3,227	104	3	67	27	7
Schuylkill R.	4,905	124	8	37	33	46
Brandywine/Christina	1,453	37	2	1	8	26
Del. R. above Wilmington	1,264	32	1	15	11	5
Del. Bay at Prime Hook	1,896	13	1	1	2	9
Delaware Basin	30,477	**442**	**44**	**130**	**138**	**130**

We constructed marginal abatement cost curves (Figures 20 and 21) that illustrate the least costs to reduce nitrogen loads by median 32% within a range of 20% (25th percentile) to 48% (75th percentile). Based on the nitrogen MAC curve, 90% of the nitrogen 13.6 million kg N/yr (30 million lb N/year) can be removed for just 35% ($160 million) of the $449 million total cost. The remaining 0.9 million kg N/year (2 million lb N/year) or 10% of the N load reduction will require 65% ($290 million/year) 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

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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 costly atmospheric and urban/suburban controls provided a diminishing rate of return in terms of pollutant removal efficiency per dollar spent.

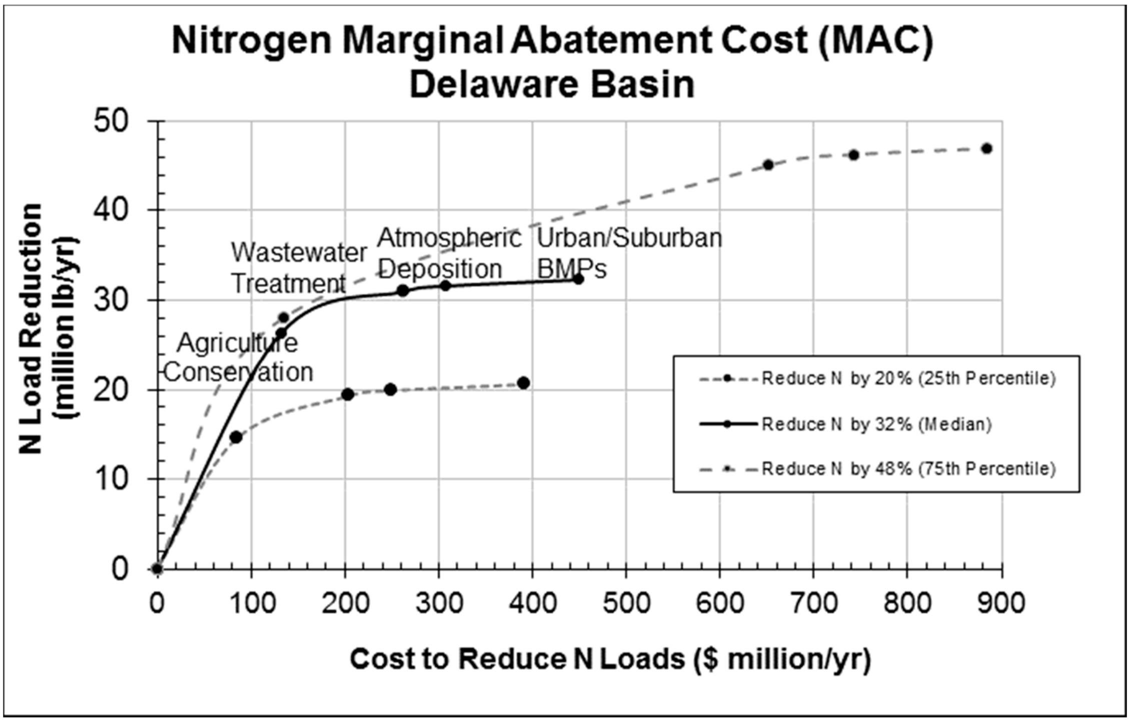

Figure. 20. Nitrogen marginal abatement cost curves in the Delaware Basin

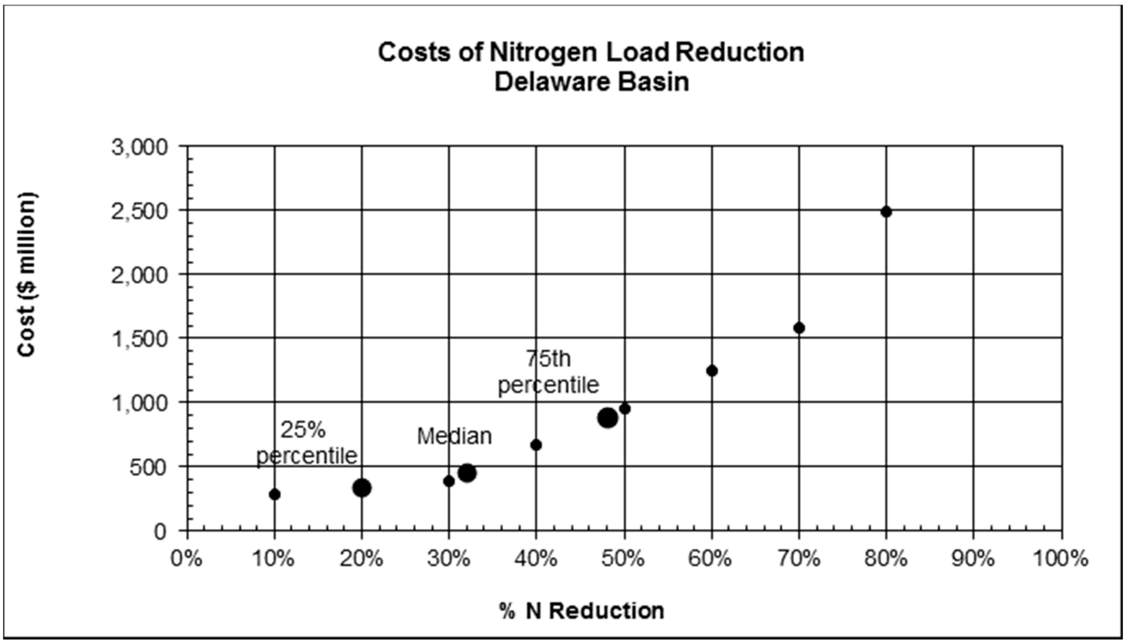

Figure 21. Nitrogen reduction cost curve for the Delaware Basin ($2010)

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6. Discussion

Adjusting to 2010 dollars and starting from a base dissolved oxygen level of 3 mg/l, our review of the 1966 Delaware Estuary economic study indicates the annual costs to improve water quality ranged from $58-$87 million to achieve summer DO of 4.0 mg/l to $180-209 million to reach 4.5 mg/l (Table 8). These estimates from the 50-year old economic study correspond well with our 21st century least cost (Option 5) that indicates $50 million/year would need to be invested to reduce pollutant loads to improve dissolved oxygen levels to 4.0 mg/l. A cost of $150 million/year would be needed to reach a DO level of 4.5 mg/l, and $449 million would be needed to reach a DO level of 5.0 mg/l in the Delaware River.

Table 8. Comparison of costs to meet water quality criteria along the Delaware River

Objective	**Summer DO (mg/l)**	**Costs ($2010) ($M/yr)**	
		FWPCA (1966)[1]	**Modern Study (2017)**
	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.

We point out an important consideration concerning the inverse relationship between dissolved oxygen saturation and water temperature in the Delaware River (Figure 22). The costs of achieving improved water quality in the Delaware River to meet more stringent dissolved oxygen criteria are based on conditions where water temperatures peak near 30°C (86°F), usually in July and August. At 30° C, freshwater DO 100% saturation is 7.54 mg/l and DO is 46% saturated at 3.5 mg/l, 53% saturated at 4.0 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 to be developed by the DRBC that would explore the influence of water temperature and salinity on dissolved oxygen in the Delaware Estuary.

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 would 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.

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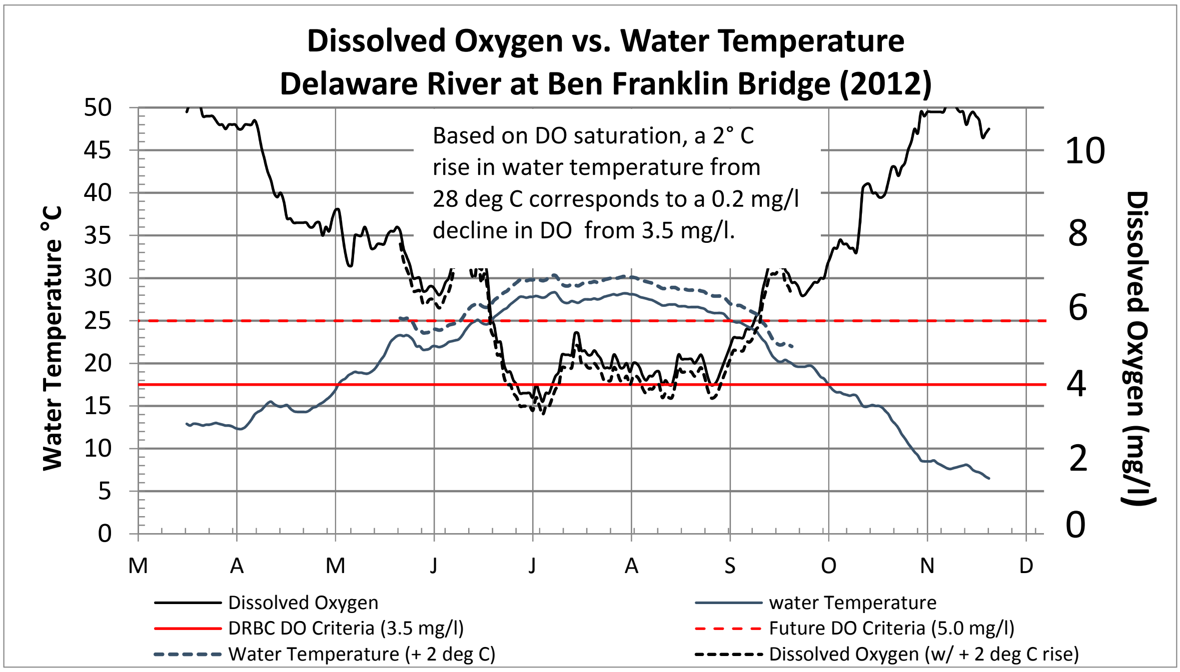

Figure 22. Dissolved oxygen/water temperature along the Delaware River at Ben Franklin Br.

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 to the bay via surface runoff [51]. Depending on soil permeability, it could take years for nutrients such as N and P in groundwater to reach the Delaware Estuary from source waters [52]. 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 9) The SPARROW model does not account for direct contributions of nitrogen from groundwater therefore it is likely that nitrogen loads to the tidal Delaware River 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 9. 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	Days to Weeks	Days to Weeks	Days to Weeks	Days to Weeks
Wastewater Treatment	Days to Weeks	Days to Weeks	Days to Weeks	Days to Weeks
Urban/Suburban BMPs				
Surface Water Runoff	Months	Days to Weeks	Days to Weeks	Days to Weeks
Groundwater Recharge	Years	Months to years	Months	Months
Agriculture Conservation				
Surface Water Runoff	Months	Days to Weeks	Days to Weeks	Days to Weeks
Groundwater Recharge	Years	Months to years	Months	Months

7. Conclusions

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.

While the water quality in the Delaware River has recovered over the last half century, The Partnership for the Delaware Estuary Science and Technical Advisory Committee (PDE STAC) has 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, we estimate that the annual costs to reduce nitrogen loads by 32% in the Delaware Basin are reduced 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%). Our interpretation of nitrogen marginal abatement cost (MAC) curves show that 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.

Our economic analysis concludes that it is be cost-effective to prioritize agricultural conservation and wastewater treatment investments in the Delaware River watershed to reduce 90% of the pollutant load by 13.6 million kg/year of nitrogen (30 million lb/year) for $160 million at 35% of the estimated $449 million annual cost. We estimate the annual costs to reduce nitrogen loads and increase dissolved oxygen to meet a more stringent standard in the Delaware River include $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. Estimates from this 50-year old economic study correspond well with our 21st century least cost analysis (Option 5) that estimates $50 million/year would need to be invested to reduce nutrient loads for dissolved oxygen levels to increase to 4.0 mg/l, $150 million/year would be needed for DO to reach 4.5 mg/l, and $449 million/year would need to be invested for DO to reach 5.0 mg/l in the Delaware River.

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