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Benefit-cost analysis of water quality policy and criteria in the Delaware River

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Abstract

This research conducts a benefit-cost analysis of water policies to reach an optimal level of dissolved oxygen (DO) to meet year-round fishable water quality criteria in the Delaware River. A watershed pollutant load model is utilized to estimate marginal cost curves of water quality improvements to meet a more protective year-round fishable standard and annual benefits are defined to achieve future DO criteria in the Delaware River. The most cost-effective DO standard is 4.5 mg/L defined by the point where the marginal benefits of willingness to pay (WTP) for improved water quality equals the marginal costs of pollution reduction. This optimal criteria (4.5 mg/L) can be achieved at a cost of $150 million with benefits ranging from $250 to $700 million/year. While a future DO standard of 4.5 mg/L reflects an economically efficient level of water quality, this DO criteria is less protective than the level of 5–6 mg/L needed to protect anadromous fish such as the Atlantic sturgeon. The policy to reach a DO level of 6 mg/L (at 80% DO saturation) may be difficult to achieve at summer water temperatures that approach 30 °C in the Delaware River at Philadelphia.

Keywords: Benefit-cost analysis; Economics; River basin; Water quality

Introduction

Clean water is an environmental good that has the economic value because people are willing to pay for it (Thurston *et al.*, 2009). The benefit-cost analysis (BCA) is often employed in water resources management to determine whether a project should be done (Thacher *et al.*, 2011). BCA helps to determine whether it is worthwhile for governments to spend on watersheds and river basins (Douglas & Taylor, 1999). BCA is a decision tool employed by policymakers to measure the net gain or loss to society due to a certain policy or project (Thurston *et al.*, 2009). Goldberg (2007) offered BCA valuation as an efficient way to make cost-effective decisions by policymakers and create a market to fund watershed services. BCA evaluates the opportunity costs of policy actions and determines whether the benefits will leave everyone well off without harm, the Pareto criterion. Policies that maximize net benefits to

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society (those who live along the Delaware River, for instance) are considered the most optimal (Boardman *et al*., 2006).

A half-century ago, the Harvard Water Program (1971) advocated planning water resources projects based on optimizing social, environmental, and economic costs/benefits (Maass *et al*., 1962). The Harvard Water Program advocated for the efficient river basin authority, such as the Delaware River Basin Commission (DRBC), as a 'legal expedient' to analyze the benefits and costs of water pollution control programs and levy fees to finance operations and provide economic incentives for dischargers to reduce pollutant loads into the river (Dorfman *et al*., 1972).

In 1965, Congress passed the Water Resources Council Act that defined Federal criteria for multi-objective cost-benefit analysis and advocated national water planning objectives based on sustainable goals of economic prosperity, environmental health, and social equity (USWRC, 1983; Stakhiv, 2011). Schaumburg (1967) examined the policies of a river basin authority (the DRBC) and Pareto efficient economics of water quality control to reduce discharger waste loads through treatment technology, effluent standards, and effluent fees and charges. The USWRC (1983), Lyon & Farrow (1995), and Daly & Farley (2011) recommended the use of BCA methods such as net benefits, marginal abatement cost curves (MAC), and marginal benefits (MB)/marginal cost (MC) curves to more efficiently restore waterways given economic and budget constraints. When MC equals MB, then investments in water pollution control will have reached optimal scale based on this BCA methodology.

Building on the work in Cambridge, Kneese & Bower (1984) from Resources for the Future in Washington, DC, explored the river basin commission as the ideal basin-wide firm to deliver economic efficiencies in water quality management. The river basin firm was envisioned as a central agency responsible for operating in competitive markets or where public authorities set prices equal to marginal costs. By assuming ownership of these measures, the river basin firm would 'internalize' the inefficient externalities of conventional water resources management. In response to a series of droughts and floods, the U.S. Army Corps of Engineers thought about resurrecting the economic and environmental benefits model first offered during the 1960s by the Harvard Water Program and Water Resources Council Act (Reuss, 2003).

Faced with tightening budgets in recent decades, government agencies must make difficult decisions about how to allocate public investments to restore the natural environment. Federal water agencies such as the US Department of Agriculture (USDA), Environmental Protection Agency (EPA), and National Oceanic and Atmospheric Administration (NOAA) use BCA to accomplish more in an era of lean budgets to (1) compare the benefits of different watershed projects and programs, (2) prioritize and allocate public spending on watershed restoration projects, (3) justify to Congress that investments maximize watershed restoration benefits per dollar spent, (4) identify tradeoffs between restoration costs and benefits due to improved water quality, and (5) decide how to allocate public spending on conservation, preservation, or restoration.

In 2012, the EPA National Center for Environmental Economics reviewed the use of benefits transfer and nonuse value methods employed by EPA since the 1980s to define monetary benefits from improved water quality (Griffiths *et al*., 2012). In 1981, Ronald Reagan issued Executive Order 12291 that required BCA for proposed regulations with costs of more than $100 million/year as designated by the Office of Management and Budget (OMB). Since then, every President has required BCA of all major proposed regulations. To comply with Executive Order 12291, the EPA has conducted BCA using WTP methods for many surface water regulations enacted between 1982 and 2009 (Table 1).

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Table 1. Synthesis of EPA BCA of surface water regulations (Griffiths *et al.*, 2012).

Date	Regulation	Pollutants	Benefits category
1982	Iron and Steel Manufacturing	TSS, pH, oil	Benefits of water pollution control
1987	Organics, Plastics, Synthetic Fibers	BOD, TSS, 128 toxics	Nonuse recreation benefits (Carson & Mitchell, 1993) and avoided costs
1995	Great Lakes Water Quality Guidance	29 toxics	Wildlife viewing (Walsh *et al.*, 1992)
1998	Pharmaceuticals	32 toxics	Water quality exceedances and nonuse as 50% of use benefits
2000	California Toxics Rule	23–57 toxics	Saltwater fishing, nonuse 50% of use benefits
2003	Metal Products and Machinery	TSS, oil/grease	Recreation benefits of improved wildlife viewing and boating (Bergstrom & Cordell, 1991), nonuse as 50% of use benefits
2004	Meat and Poultry Products	TSS, oil/grease, N, P, coliform	Nonuse recreation (Carson & Mitchell, 1993) and avoided costs of drinking water treatment
2006	Cooling Water Intake Structures	Impacts to aquatic life	Recreation benefits of increased fish catch from a random utility model increased commercial fish harvest from market prices
2009	Construction and Development	TSS, turbidity	Recreation nonuse from the regression of 45 studies and avoided costs for dredging and drinking water treatment

Research objectives

Little is known about the modern cost-effectiveness of investing in water pollution abatement programs that increase dissolved oxygen (DO) levels and achieve improved water quality in the Delaware River. This research conducts a modern 21st century BCA of water pollution abatement efforts that result in an optimal level of DO to meet year-round fishable water quality standards in the Delaware River. This work compares the costs and benefits of water pollution control programs in the Delaware Basin that improve water quality and achieve a future, more protective DO standard that would support year-round propagation of anadromous and domestic fisheries in the river. This work examines the optimal or most cost-effective level of water quality (DO) in the Delaware River defined by the intersection of the MC and MB curves or the point where the MC of pollution reduction programs equal MB of improved water quality (Figure 1).

The following BCA compares the costs to reduce nitrogen loads from wastewater, atmospheric deposition, urban/suburban, and agriculture sources with benefits from WTP for improved water quality in the Delaware River, all in $2010. This BCA updates a 1960s Delaware River economic study (FWPCA, 1966; Kneese & Bower, 1984) conducted by the Federal Water Pollution Control Administration (a forerunner to EPA) and incorporates modern ecological economics methods such as MB/MC curves to assess benefits based on WTP for improved water quality. Once the costs and benefits of improved water quality are known, various funding mechanisms can be examined to pay for water pollution control programs under the umbrella of a Federal-state river basin organization.

The Delaware River Basin

The 13,000 square miles, 300-mile-long Delaware River Basin (Figure 2) covers just 0.4% of the conterminous United States yet supplies drinking water to 13 million people (5% of the nation's population) and the

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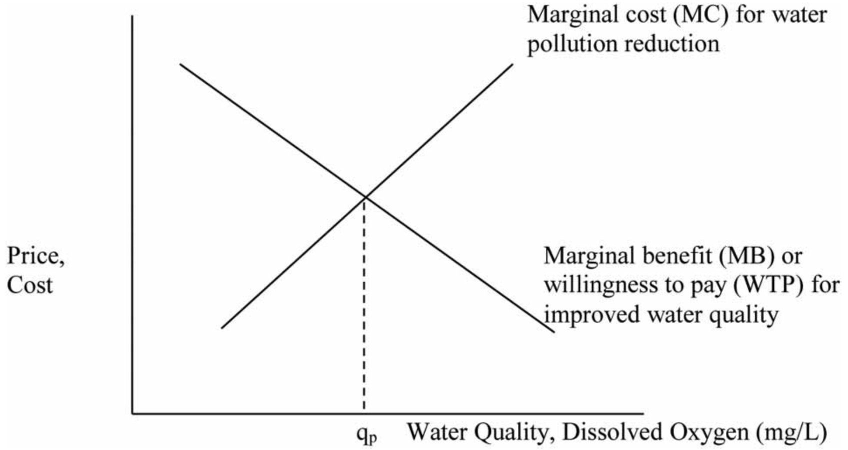

Fig. 1. Optimal water quality.

first (New York City) and seventh-largest (Philadelphia) metropolitan economies in the nation. The Delaware Basin contributes over $22 billion in annual economic activity in the four states and is directly/indirectly responsible for over 500,000 jobs in Delaware, New Jersey, New York, and Pennsylvania (Kauffman, 2016).

After the Second World War, the river was severely polluted with DO levels near zero between Wilmington and Philadelphia due to unregulated dumping of untreated sewage, coal mine drainage, and agricultural and urban runoff. During the 1950s, the polluted river prevented the spawning of American shad past the zero oxygen block upstream from Wilmington and threatened Philadelphia's drinking water supply. In the early 1960s, the Federal Water Pollution Control Administration (1966) conducted an economic study of proposed waste load reductions and concluded that water supply and river recreation benefits due to improved water quality would exceed proposed wastewater treatment costs.

The river began to recover after passage of the Delaware River Basin Commission (DRBC, 1961) Compact of 1961 and Federal Clean Water Act Amendments of 1972 and 1977 (Albert, 1988). In 1967 when the river was anoxic (DO levels at zero), the DRBC considered the 1966 FWPCA BCA and set the summer DO standard at 3.5 mg/L (the current standard) in the Delaware River between Philadelphia and Wilmington to provide for spring/fall migration (not year-round propagation) of anadromous fish (DRBC, 2015). The DRBC adopted the first interstate water quality standards and in 1968 imposed waste load allocations on 80 dischargers, a half-decade before Congress passed the Clean Water Act Amendments of 1972. With improved water quality, the Delaware River now supports a growing drinking water, fishing, boating, and recreation economy.

The Delaware has a long history of nutrient pollution, but DO levels in the river have recovered considerably in the last several decades (Bain *et al.*, 2010). Since 1970, the DRBC has conducted monthly boat run surveys that indicate summer DO levels have improved in the Delaware River between Wilmington at mile 70 and Philadelphia at mile 100 (Figure 3). Most readings now exceed the 3.5 mg/L DO standard, however, a subtle decline in DO occurred during the first 5 years of the 21st century (a convex effect), which was a troubling reversal from the early successes since the 1970s and 1980s.

While water quality has measurably improved in the tidal Delaware River between Wilmington and Philadelphia since the signing of the DRBC Compact in 1961, DO levels occasionally approach and fall below the DRBC standard (3.5 mg/L) during summer. Secor & Gunderson (1998) and Campbell & Goodman (2004) and others have concluded that minimum DO criteria of 3.5 mg/L are not adequate to

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Fig. 2. The Delaware River Basin.

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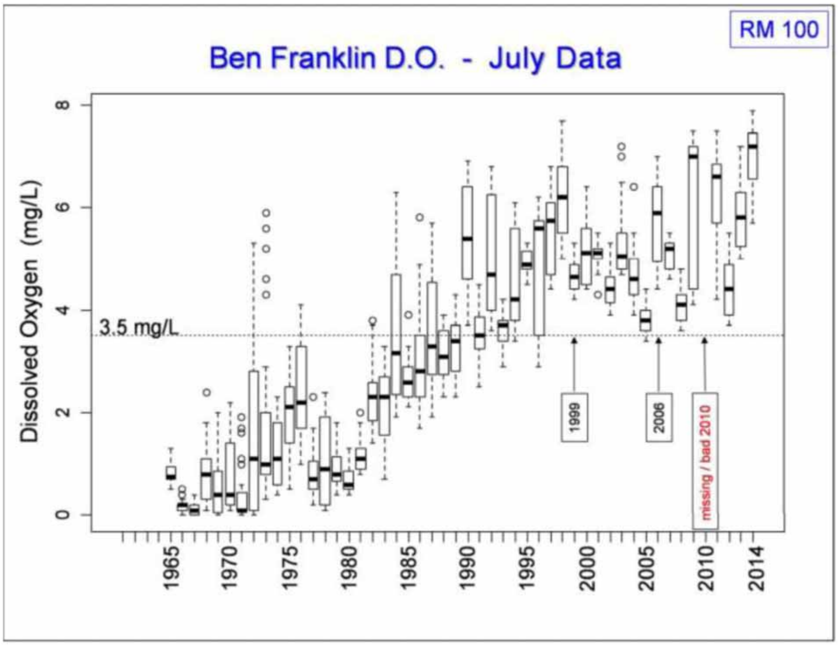

Fig. 3. July DO levels along the Delaware River at Ben Franklin Bridge (DRBC, 2015).

sustain anadromous fish, such as Atlantic sturgeon and shortnose sturgeon, in the river. In 2017, the DRBC passed a resolution that 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 and plan for atmospheric warming that would increase water temperatures and boost salinity due to sea-level rise which, in combination, would decrease DO saturation.

1960s Economic analysis

During the 1960s, the Federal Water Pollution Control Administration (1966) issued a Delaware Estuary Comprehensive Study as one of the first economic analyses in the nation that evaluated the costs and benefits of achieving water quality goals (Thoman, 1972; DeLorme & Wood, 1976; Kneese & Bower, 1984). The 1966 FWPCA study estimated wastewater load reduction costs ranged from $100 to $150 million to meet a summer DO goal of 2.5 mg/L and $490 million to meet a summer DO goal of 4.5 mg/L to fully sustain an anadromous shad fishery in the Delaware River near Philadelphia (Table 2). Benefits ranged from $120 to $280 million to meet a DO goal of 2.5 mg/L and $160 to $350 million to meet a DO goal of 4.5 mg/L in the Delaware River. Objective Set III appeared to be a most cost-effective option as maximum net benefits are highest ($130 million) to achieve a DO level of 3 mg/L that would allow 80% shad survival during the spring spawning cycle (Figure 4). In 1967, a DRBC water use advisory committee of industry, government, recreation, and conservation stakeholders examined the FWPCA BCA and adopted a combination of Objective Sets III (3 mg/L) and II (4 mg/L) as the most cost-effective option and set the summer 24 h DO standard at 3.5 mg/L for the Delaware Estuary water quality zones between Wilmington and Philadelphia (DRBC, 2015). The current 3.5 mg/L DO standard set by the DRBC has stood for over 50 years along the tidal Delaware River.

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Table 2. Costs and benefits to meet water quality objectives in the Delaware Estuary (FWPCA, 1966; Thoman, 1972).

Objective set	Summer DO (mg/L)	BOD/COD residual (lb/day)	% Pollution removal	Costs ($1964) ($ million)	Benefits ($1964) ($ million)	Net benefits ($1964) ($ million)	% shad survival passage
I	4.5	100,000	98	490	160–350	−230 to −140	98
II	4.0	200,000	90	230–330	140–320	−90 to −10	90
III	3.0	500,000	75	130–180	130–310	0–130	80
IV	2.5	500,000	50	100–150	120–280	20–130	50
V	0.5	*Status quo*		30	0	−30	20

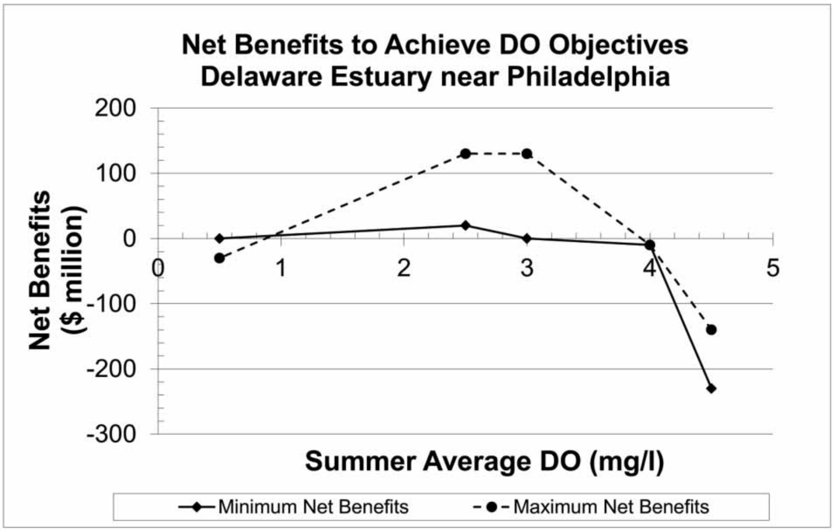

Fig. 4. Net benefits in 1966 to achieve DO objectives in Delaware Estuary near Philadelphia (FWPCA, 1966).

Methods

The BCA of attaining year-round fishable water quality standards in the Delaware River was conducted by (1) estimating the annual costs of reducing nutrient loads in the basin that would lead to improved DO levels in the tidal river (Kauffman, 2018), (2) measuring the annual benefits of improved water quality in the viewing/boating/fishing recreation, commercial fishing, agriculture, navigation, property value, and water supply and nonuse value sectors, and (3) plotting MB/MC of attaining improved water quality as measured by DO in the river.

Costs

Costs of nitrogen pollutant load reductions were estimated that would increase DO from current criteria (3.5 mg/L) to a future, more stringent water quality standard (of 4.0, 5.0, or 6.0 mg/L) in the Delaware River (Kauffman, 2018). Costs were based on controls for five options needed to achieve a median 32% reduction in nitrogen estimated from the Delaware River Basin total maximum daily

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load (TMDL) models (Scatena *et al*., 2006) within confidence intervals ranging from 20% N reduction (25th percentile) to 48% N reduction (75th percentile). Nitrogen load reduction costs were determined by the following methods: (1) quantified nitrogen loads in the Delaware Basin using the USGS SPAtially Referenced Regressions on Watershed (SPARROW) model (Moore *et al*., 2011) from atmospheric, urban/suburban, wastewater, and agricultural sources and estimated pollutant load reductions needed to improve DO in the Delaware River from current 3.5 mg/L to future more protective standard, (2) estimated costs of nitrogen load reductions to improve DO levels in the tidal Delaware River for various best management practice 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, and (3) constructed marginal abatement cost curve to define annual least costs to raise DO levels to more stringent fishable criteria by multiplying N load reduction rates (kg/year) by the unit cost ($/kg) in $2010 for atmospheric NO_x 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.

Benefits

Benefits of attaining improved water quality standards along the Delaware River were defined by the market and nonmarket use value of viewing/boating/fishing recreation, commercial fishing, agriculture, navigation, property value, and water supply and the nonuse value based on WTP for boatable/fishable water quality (Kauffman, 2019). Economic benefits of improved water quality are estimated for recreational boating, fishing, bird watching, waterfowl hunting, and beach going using a five-step approach. First, the number of visitors who participated in recreational activities in each state in the Delaware Basin is determined. Second, statewide estimates of recreational participants were scaled to the watershed level by the proportion of the population and/or land area within each state. Third, the literature was reviewed to select appropriate unit day values per person for each recreation activity. Fourth, the existing value of each activity was selected by multiplying the unit day value by the number of recreation visits. Fifth, benefits were estimated by multiplying the existing value by the percentage change in value due to improved water quality.

Travel cost models were employed to estimate the benefits of improved water quality to go from nonsupport (impaired) to viewing, boatable, and fishable uses in the Delaware River. Swimmable benefits were not considered as very few safe opportunities for swimming exist along the Delaware River due to strong tidal currents, lack of accessible beaches, and high bacteria levels that exceed DRBC primary contact recreation criteria. Annual recreation benefits were calculated to achieve boating and fishing water quality by selecting per person values from travel cost studies and multiplying by the U.S. Census adult population (>18 year old). The value of recreation due to improved water quality was estimated using the unit day value method by multiplying the number of visitor days by the unit value ($/day) of a recreation day. Recreation benefits of improved water quality are measured by the increase in the number of activity days (Leeworthy & Wiley, 2001) by participants at the river.

The stated preference approach includes the contingent valuation (CV) method that asks people how much they would be WTP for improved water quality for viewing, boating, fishing, and swimming (Emerton & Bos, 2004; Kramer, 2005; Thurston *et al*., 2009). Revealed preference methods estimate the increased sale or purchase of goods or reduced costs that result from improved water quality and include the market price, productivity, damage cost avoided, travel cost, and hedonic pricing methods. The travel cost

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method defines the higher costs that visitors are WTP for trip and equipment expenditures to participate in more frequent recreation tourism, boating, hunting, fishing, and birding trips due to improved water quality (Smith & Desvousges, 1986; Freeman, 2003). The hedonic pricing method indirectly measures benefits by recording the higher value of property close to rivers and bays with improved water quality.

Benefit-cost analysis

Cost-effective approaches to reduce pollution loads and attain water quality standards in the Delaware River were defined by (1) calculating MC of reduced pollutant loads that result in improved water quality as DO in the river increases from 3.5 to 4.0 mg/L, 4.5 to 5.0 mg/L, and so forth, (2) calculating net benefits as water quality improves from the DO level of 3.5 to 4.0 mg/L, etc., and (3) calculating net benefits (total benefits minus costs) and the benefit–cost (B/C) ratio. A cost/benefit curve was constructed where the intersection of the MC and MB or WTP curve defines the level of optimal water quality (q_p) measured by DO in the Delaware River. The marginal cost is defined as the additional cost from one more unit purchased such as a pound of nitrogen reduced. Marginal benefit is the additional benefit from one more unit consumed such as improved water quality (Thurston *et al.*, 2009).

Results

Costs

Annual costs were $334, $449, and $904 million, respectively (Figure 5), to reduce nitrogen loads by 20% (25th percentile), 32% (median), and 48% (75th percentile) that would improve DO levels in the

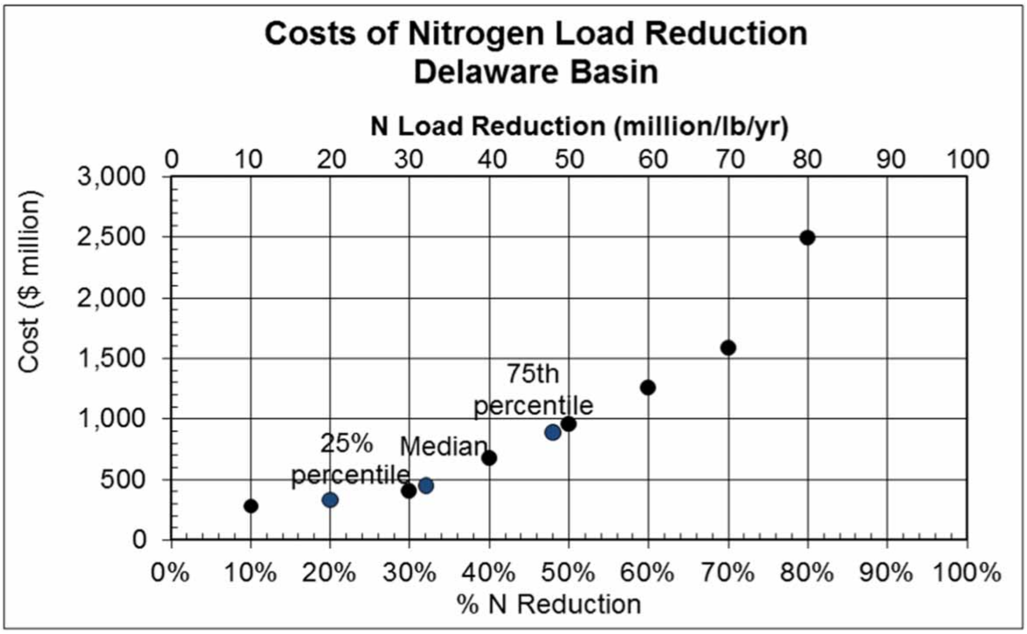

Fig. 5. Nitrogen reduction cost curve for the Delaware Basin in $2010 (Kauffman, 2018).

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Delaware River to at least 5.0 mg/L (Kauffman, 2018). By maximizing least-cost agricultural and wastewater reduction practices and minimizing higher-cost airborne emissions and urban stormwater controls, annual costs to reduce N loads by 32% in the Delaware Basin are reduced from $1.66 billion for Option 1 that would reduce nitrogen from all sources evenly by 32% to $449 million for the least cost Option 5 that would to reduce agricultural nitrogen by 90% and reduce the other sources by 5–10% (Table 3).

Benefits

Annual benefits due to attaining an improved water quality standard in the Delaware River from a DO level of 3.5 m/l presently to a future criteria of 5.0 mg/L range from a low bound of $370 million to a high bound of $1.1 billion in $2010, as summarized in Table 4 (Kauffman, 2019). Recreational viewing, fishing, and boating provide 45% of benefits followed by agriculture (17%), nonuse WTP (10%), wildlife/birdwatching, waterfowl hunting, and beach recreation (6%), water supply (4%), and commercial fishing, navigation, and property value benefits each at 2% of the total.

Benefit-cost analysis

A cost-effective level of water quality in the Delaware River as measured by DO occurs at 4.5 mg/L where maximum net benefits (benefits minus costs) range from $100 to $550 million/year (Table 5). At a DO level of 5.0 mg/L, higher net benefits ($610 million/year) occur for the high bound curve, yet net

Table 3. Costs in $2010 of nitrogen load reduction in the Delaware River (Kauffman, 2018).

Nitrogen reduction option	Atmospheric deposition	Wastewater treatment	Urban/Suburban BMPs	Agricultural conservation	Total
1. Reduce N by 32% all sources	32%	32%	32%	32%	32%
N reduction (kg/year)	1,759,937	6,746,727	2,053,865	4,253,786	14,814,315
Cost ($ million/year)	291	416	905	47	1,660
2. Reduce Ag N by 32%	5%	47%	5%	32%	32%
N reduction (kg/year)	274,877	9,910,078	321,143	4,253,786	14,758,976
Cost ($ million/year)	45	612	141	47	846
3. Reduce Ag N by 60%	5%	29%	5%	60%	32%
N reduction (kg/year)	274,877	6,114,420	321,143	7,975,055	14,685,495
Cost ($ million/year)	45	377	141	88	652
4. Reduce Ag N by 75%	5%	20%	5%	75%	32%
N reduction (kg/year)	274,877	4,216,591	321,143	9,969,045	14,781,656
Cost ($ million/year)	45	260	141	110	557
5. Reduce Ag N by 90%	5%	10%	5%	90%	32%
N reduction (kg/year)	274,877	2,108,296	321,143	11,963,035	14,667,351
Cost ($ million/year)	45	130	141	132	449

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Table 4. Benefits of improved water quality in the Delaware River in $2010 (Kauffman, 2019).

		Existing DO (3.5 mg/L) ($ million/year)		Future DO (5 mg/L) ($ million/year)	
Category	Activity	Low	High	Low	High
Use					
Recreation	Viewing, Boating, Fishing	4.5	5.6	55	68
	Boating	159	350	46	334
	Fishing	216	337	129	202
	Shad fishing	0	6.5	0	3.9
	Bird/Wildlife Watching	307	325	15	33
	Waterfowl Hunting	1.4	16	0.1	1.6
	Swimming	0	0	0	0
	Beach Going	6	50	2	16
Commercial	Fishing	34	34	0	17
	Agriculture	0	0	8	188
	Navigation	81	81	7	16
Indirect use	Property Value	333	333	13	27
Water supply	Municipal Water Supply	196	196	12	24
	Industrial Water Supply	140	140	8	17
Nonuse					
Existence/Bequest	WTP Boatable to Fishable WQ	102	151	76	115
Total		1,580	2,025	371	1,063

Table 5. BCA of attaining improved water quality in the Delaware River.

DRBC DO criteria	DO (mg/L)	32% N reduction (kg/year)	Costs ($ million)	Marginal Costs ($ million)	Benefits ($ million)		Marginal benefits ($ million)		Net benefits ($ million)		*B*/*C*	
					Low	High	Low	High	Low	High	Low	High
Existing	3.5	0	0	0	0	0	370	1,060	0	0	0	0
↓	4.0	4,900,000	50	50	120	350	250	710	70	300	2.4	7.0
	4.5	9,800,000	150	100	250	700	120	360	100	550	1.7	4.7
Future	5.0	14,667,351	450	300	370	1,060	0	0	−80	610	0.8	2.4

benefits are negative for the low bound curve. Based on the *B*/*C* ratio, the most cost-effective level of DO may be achieved at 4.0 mg/L where *B*/*C* ratios are highest ranging from 2.4 to 7.0.

Optimal water quality in the Delaware River occurs where the MC curve intersects the MB curve or the point where the economic system is in equilibrium (Figure 6). The MC and MB curves illustrate five cost options based on a nitrogen reduction of 32% and low and high bound benefits curves. The five MC curves fan out and intersect the low bound MB line at a DO level between 4.3 mg/L for Option 1 and 4.6 mg/L for Option 5. The five MC curves also intersect the high bound MB line at a DO level between 4.5 mg/L (Option 1) and 4.7 mg/L (Option 5). The intersections of these MC/MB curves suggest that the optimal level of DO is close to 4.5 mg/L.

Based on the BCA, the optimal level of water quality in the Delaware River as measured by DO ranges from 4.2 to 4.8 mg/L. A DO level of 4.2 mg/L could be achieved at a cost of $90 million

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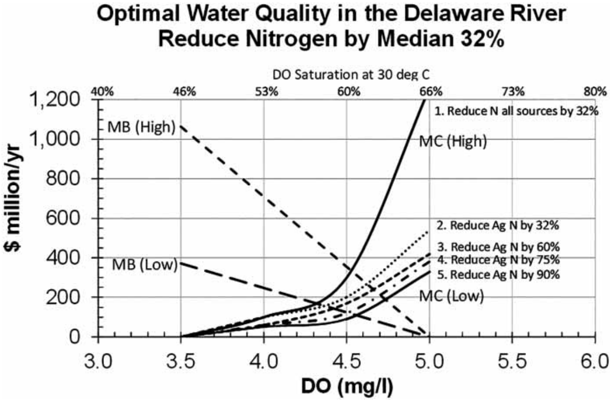

Fig. 6. MC and MB of optimal water quality in the Delaware River.

with benefits of $170–$490 million/year. A DO level of 4.5 mg/L could be achieved at a cost of $150 million with benefits of $250–$700 million/year. A DO level of 4.8 mg/L could be achieved at a cost of $360 million with benefits of $320–$920 million/year. If administrative efficiency in implementing water quality regulations is desired, then the optimal or economically efficient future DO standard could be rounded to 4.5 mg/L.

Discussion and conclusions

An economically efficient level of DO in the Delaware River (4.5 mg/L) must be balanced with the protective levels needed for the propagation of anadromous fish, given that DO saturation is inversely related to water temperatures that approach 30 °C (86 °F) during the hot summer months. At an annual cost of $150 million, a future DO standard of 4.5 mg/L in the tidal Delaware River would reflect an economically efficient level of water quality at the equilibrium point near where the MC equals the MB. On the other hand, an economically efficient criterion of 4.5 mg/L would be less protective than the minimum DO level of 6 mg/L that the literature suggests is needed for the year-round propagation of anadromous fish such as the sturgeon. However, a DO level of 6 mg/L (80% DO saturation) may be difficult to achieve at summer water temperatures that approach 30 °C in the Delaware River at Philadelphia (Figure 7). At 30 °C, freshwater DO saturation ranges from 46% at 3.5 mg/L to 66% saturated at 5.0 mg/L and 100% at 7.54 mg/L. A DO standard of 5 mg/L (66% DO saturation) may be more readily achieved at these warm water temperatures and would be more protective than the economically efficient level of 4.5 mg/L (60% DO saturation) but will be less protective of anadromous fish than 6 mg/L (80% DO saturation).

This BCA utilized modern ecological economics techniques to define the cost-effectiveness of water pollution control measures to reduce nitrogen loads and raise DO levels to a more protective, year-round fishable standard in the Delaware River. The BCA is based on a median 32% reduction in nitrogen to the Delaware River bounded by 20% N reduction (25th percentile) and 48% N reduction (75th percentile) confidence intervals. This analysis includes five options that vary from the highest cost Option 1 (reduce N from all sources by 32%) at a cost almost four times more than the least cost Option 5 (reduce N from agriculture by 90%). A plot of the five options indicates that the MC and

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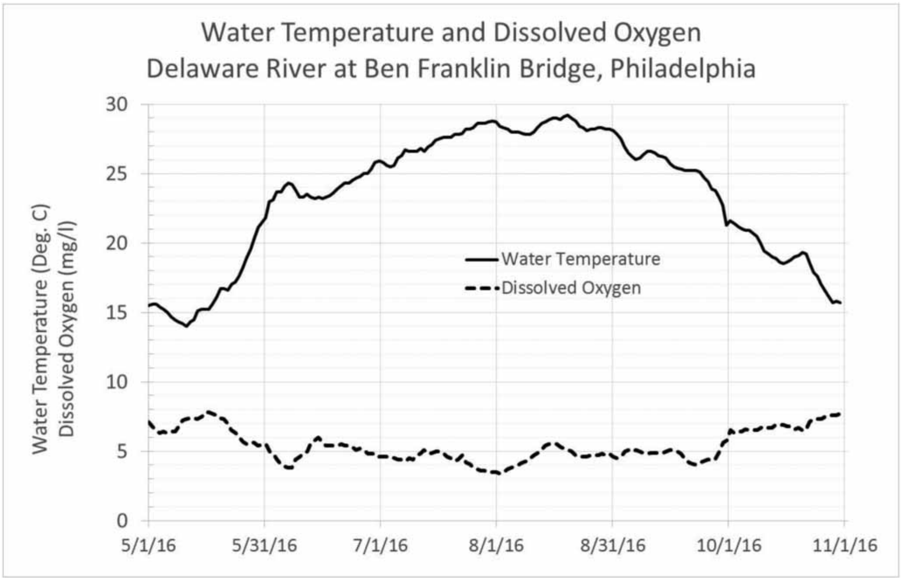

Fig. 7. Relationship between water temperature and DO along the Delaware River (USGS, 2018).

MB curves intersect just below and just above the economically efficient 4.5 mg/L DO criteria. Based on the BCA, the optimal level of water quality in the Delaware River as defined by DO of 4.5 mg/L could be achieved at a cost of $150 million with benefits of $250–$700 million/year.

This BCA raises two considerations: (1) letting the economics optimize the target may fail to ensure environmental goals (such as a stricter definition of the fishable standard) and (2) this suggests that implementation efficacies and/or costs may be critical to choosing a target that considers economics in addition to environmental conditions. Based on this economic approach, the BCA suggests several options in setting a higher DO standard in the Delaware River. The first option would establish economically efficient yet less protective DO criteria at 4.5 mg/L at a level that balances MC with MB. If $150 million/year were invested to achieve an efficient level of water quality (where MC = MB) with DO at 4.5 mg/L with benefits of $250–$700 million, the monthly cost would range from $0.96 per capita for the 13 million people who depend on drinking water from the watershed in Delaware, New Jersey, New York, and Pennsylvania to $1.52 per capita for the 8.2 million residents of the Delaware Basin. A second option would be to invest $450 million/year to achieve more environmentally protective year-round DO criteria of 5.0 mg/L with benefits of $370 million to $1.06 billion/year.

Table 6. Benefits and costs of improved water quality per capita in the Delaware Basin.

Water quality option	DO criteria (mg/L)	Cost ($ million/year)	Benefits ($ million/year)	Cost/Capita ($/month)
Economically efficient WQ (MC = MB)	4.5	150	250–700	0.96[a]–1.52[b]
Year-round fishable WQ	5.0	450	370–1,060	2.88[a]–4.46[b]

[a] Based on the population of 8.2 million who live within the Delaware Basin.

[b] Based on 13 million people who draw drinking water from the Delaware Basin.

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The monthly cost would range from \$2.88 per capita for the 13 million people who depend on drinking water from the basin to \$4.46 per capita for the 8.2 million residents of the Delaware Basin (Table 6).

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