Economic Value of Dissolved Oxygen Restoration in the Delaware Estuary

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Key Abbreviations / Terms

Hypoxia means “depression in oxygen conditions.” In freshwater and marine settings, hypoxia refers to the depression of dissolved oxygen in the surrounding waters to the point of causing stress on the aquatic organisms living in that setting. Because each organism has its own physiological tolerances and thresholds for oxygen depletion, there is no single definition for when the depression in dissolved oxygen constitutes “hypoxia.” In the current report, dissolved oxygen concentrations below 5.0 mg/L are included in the description of hypoxia. This threshold is based on the recently updated water quality standards from Pennsylvania that define the instantaneous minimum dissolved oxygen standard as 5.0 mg/L for the protection of aquatic life in flowing water settings such as the Delaware River.

Severe Hypoxia defines low dissolved oxygen conditions such that little or no aquatic life can survive for any length of time. In the current report, dissolved oxygen concentrations below 2.0 mg/L are included in the definition of “severe hypoxia.”

Anoxia means “lack of oxygen.” In freshwater and marine settings, anoxia also refers to such severe hypoxia that little or no aquatic life can persist in such conditions for any length of time. There is no agreed-upon threshold for anoxia, with the term used to describe dissolved oxygen conditions at or below values ranging from 0.0 mg/L up to 2.0 mg/L.

BOD, or Biochemical Oxygen Demand, is a derived water quality analysis endpoint that reflects the total available compounds that would result in oxygen consumption in that water sample over time. It is measured by culturing a water sample at standard conditions and recording the total cumulative oxygen that is consumed at different time intervals in the sample, typically 5, 20, or 90 days. The oxygen consumption primarily results from microbial organisms utilizing carbon and nitrogen containing compounds as an energy source (aka, food)[1]. The treatment and reduction of BOD are among the primary functions of wastewater treatment plants, where influent BOD’s ranging from 100-200 mg/L are reduced by 85% or more.

CBOD, or Carbonaceous Biochemical Oxygen Demand, is that portion of BOD in a water sample attributable to carbon, or organic, compounds. Thus, CBOD fits neatly in our traditional understanding of “food” for aerobic life. CBOD can be the dominant form of BOD in raw wastewater samples and is a major focus of the wastewater treatment cycle. Historically, CBOD was referred to as “First Stage Oxygen Demand” or FSOD. Yet not all organic compounds are readily digestible, and both “fast” and “slow” forms of organic materials create a complex mixture of CBOD in both raw wastewater and in the final treated effluent that leaves a wastewater treatment plant.

NBOD, or Nitrogenous Biochemical Oxygen Demand, is that portion of BOD in a water sample attributable to reduced nitrogen compounds. A limited suite of bacteria can use these chemically

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[1] The term “chemical” in “biochemical oxygen demand” also includes a strictly chemical reaction where oxygen is used to oxidize compounds such as sulfides and nonferrous iron, but in municipal wastewater settings such as discussed in this report, these chemical reaction components of the oxygen demand are typically considered negligible.

reduced nitrogen compounds as a food source, including the simple ammonia molecule, NH_3. The process of converting these nitrogen compounds from reduced forms to oxidized forms is known as "Nitrification" and can occur in both the environment (e.g., estuarine waters) or within controlled conditions of a treatment plant. Historically, treatment of NBOD through nitrification was not included in wastewater treatment plant designs in the initial move to "secondary treatment" and nitrification was at times considered a nuisance problem that needed to be controlled. Conventional wastewater treatment now typically includes nitrification, with low effluent concentrations of ammonia and NBOD.

Moderate Restoration and Full Restoration scenarios are predictions of future dissolved oxygen conditions (and the variability in these conditions) for the Delaware Estuary. These two scenarios are fully defined in Appendix A, including the statistical basis for these predictions. In short, the "Full Restoration" describes a scenario where the anthropogenic dissolved oxygen sag is completely eliminated for the estuary; the "Moderate Restoration" describes a scenario where a remnant dissolved oxygen sag of approximately 0.5 mg/L (~5% saturation) is still seen in the estuary, at least periodically.

Ecosystem Services (ES) are, simply and in the terms chosen by the U.S. Forest Service, "the benefits people obtain from ecosystems" (U.S. Department of Agriculture Forest Service, 2012). We prefer a definition with a little more power to guide analyses of ecosystem services:

"Ecosystem services are the effects on human well-being of the flow of benefits from *ecosystems to people* over given extents of space and time" (Johnson et al., 2010).

The italics are to emphasize that ecosystem services are about human welfare, not nature for its own sake. They are about flows of benefits (as opposed to states of nature). Ecosystem services also flow from one place to another at one time or another (they are not static). This definition is an important component of the lens through which we have viewed and evaluated the existing literature.

The Benefit Transfer Method (BTM) is a means of establishing the value of ecosystem service flows in one setting by transferring values derived through primary research in another setting. For example, if a study of the ecosystem service values of a wetland forest in one place has determined that each acre of such forest generates $1,000 per acre per year in recreational value (e.g., because it is good songbird habitat and therefore supports birdwatching, say), we might transfer that value to an acre of wetland forest in another location. This is an example of the sub-genre of BTM known as "unit value transfer" in which a single number or set of numbers is transferred from the earlier study.

Zone of Influence is associated with the property value benefit estimation. Zones of influence represent potential sale price increases in specified distances away from a river. Potential sale price increases are estimated by Netusil et al., 2014 for four zones of influence (0 to ¼ mile, ¼ mile to ½ mile, ½ mile to 1 mile, and 1-mile to 2-mile), for a more urban watershed and a less urban watershed. (See Table 5).

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Executive Summary

Water quality problems have long afflicted the 133-mile-long tidal Delaware Estuary, particularly the urban corridor from Camden, New Jersey, and Philadelphia, Pennsylvania, down to Wilmington, Delaware. The depression of dissolved oxygen (D.O.) beyond the tolerable limits of fish and other aquatic life, known as "hypoxia," has been the most acute threat to the living ecosystems in the estuary for more than 100 years, with the hypoxia driven primarily by human wasteloads. Major improvements to D.O. have been attained in the last 50 years and originate in the 1967 water quality standards promulgated by the Delaware River Basin Commission (DRBC) combined with a subsequent 1968 "pollution diet" for carbonaceous biochemical oxygen demand (CBOD, an important fraction of the wastes causing the estuary's hypoxia). Yet the failure to regulate the other important fraction of those wastes (nitrogenous biochemical oxygen demand, or NBOD) over the last 50 years has prevented full restoration of dissolved oxygen in the estuary, leading to a persistent zone of hypoxia from Philadelphia down to the Delaware state line (7 miles up-river from Wilmington) during summer months.

Increasing realization of both the opportunity for more complete restoration of dissolved oxygen levels in the estuary, and the injustice toward human communities and the estuarine ecosystem embodied in the failure to act, have produced momentum to complete the restoration of dissolved oxygen for this estuary and attain the full potential of this ecosystem. In particular, the treatment of NBOD wastes is conventional technology today, and multiple efforts are examining the restoration potential for the Delaware Estuary from implementing NBOD treatments.

In this study, we assess the effects of improved dissolved oxygen levels in the Delaware Estuary, qualitatively and quantitatively, using an ecosystem services assessment framework. Because the spatial extent of relationships between ecosystem and societal benefits is accounted for within the framework, we are able to identify where benefits accrue and consider whether they provide any particular advantage to communities where environmental injustices impacting marginalized communities and communities of color may occur. Our analysis of the economic distribution of benefits focuses on the population residing within two miles of the Delaware River and the lower tidal Schuylkill River, with a specific focus on the cities of Chester, Camden, Wilmington, and Philadelphia.

We estimate dissolved oxygen improvements under a "Moderate Restoration" scenario could stimulate ecosystem service benefits totaling $44 million to $62 million annually. This includes a one-time increase in property value ranging from $540.9 to $835.4 million, or $32.0 to $48.4 million annually. This one-time benefit would be realized in the market if households within the specific zones of influence are sold at any point in the future. Furthermore, investing in methods to improve dissolved oxygen could be a catalyst for economic uplift in vulnerable communities, and an important component of this analysis is understanding how and where benefits may accrue. Single family residential properties within Philadelphia could see the most gains, collectively between $313.5 to $326.1 million or $19.6 to $20.4 annually. In Camden, Chester, and Wilmington there could be collective gains of $6.8 million to $17.3 million, or $300,000 to $1 million annually.

In addition to this one-time benefit under the same Moderate Restoration scenario, a 1 mg/L (or greater) improvement in dissolved oxygen levels would provide economic benefits to fisheries and recreational users in the estuary. The potential increase in commercial ex-vessel values[2] resulting from improved juvenile survival rates for three species, American shad, striped bass, and white perch, in the Moderate Restoration scenario could be $728,000 annually, depending on the harvest and the D.O. statistic used for the fishery uplift, with market values substantially greater. Recreational benefits from increased water quality (and improved dissolved oxygen levels) corresponding to increases in anglers' catch per fishing trip for the three study species could range from $3.3 million to $5.8 million annually for an expected increase of 0.5 fish or 1 fish per trip, respectively. Benefits of improved water quality for river-related recreation by residents of the study region range from $3.5 million a year for shoreline activities to $4.0 million for boating.

Our modeling captures many of the key societal benefits, but others are not estimable at this time. As a result, our analysis represents a conservative estimate of overall economic benefits. Data on the relationship between juvenile survival rates and dissolved oxygen levels for other estuary species would be required to estimate broader fisheries benefits. In addition, reliable, estuary-specific data for the species and number of fish kept by recreational anglers, commercial property value, non-single family/non-owner occupied residential property value, participation in recreational activities in addition to boating and viewing, and non-use values such as option and bequest[3] are important to estimate total benefits which would be greater than those provided here.

Estimates of additional financial, environmental, and social costs should be considered by policymakers when considering the tradeoffs between costs of D.O. improvements and the economic and environmental sustainability of the Delaware River watershed. Restoring water quality could bring a cascade of benefits to all communities within the estuary. There are likely positive environmental justice implications as it may engender economic opportunities and improvements in social conditions in economically disadvantaged communities. Traditional cost-benefit analyses do not focus enough on the holistic value of restoration, primarily in communities facing environmental injustices. Therefore, because our analysis is spatially explicit, future policies should aim to consider equity concerns and ensure historically underserved communities have equal access to tools and opportunities provided to more affluent communities in the estuary so that environmental justice can be achieved.

Beyond the scientific value of the information developed, the results of our research can inform and guide the implementation of Delaware River restoration efforts, as well as allied efforts to leverage improved water quality into enhanced economic development opportunities in riverside and nearby communities.

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[2] Ex-vessel value is defined as the price received at the point of landing for the catch (NMFS, 2018).

[3] Option value refers to the value individuals place on preserving a natural resource, even if they are uncertain if or when they will use it. Bequest value refers to the value of preserving natural resources for the benefit of future generations.

Overview of The Delaware Estuary and Water Quality

Water Quality Conditions & History for the Delaware Estuary

The Delaware Estuary is a vibrant ecosystem with a host of plant and animal species living and reproducing in its array of unique and varied habitats. Beginning at the Atlantic Ocean and extending 133 miles upstream to the head-of-tide at Trenton, New Jersey, the saltwater to freshwater transitions define major regions and distinct ecological communities of the Delaware Estuary. Beginning at the upper end, the freshwater tidal river extends approximately 50 miles downstream from Trenton through Philadelphia and Camden to near the Delaware state line. The brackish water transition begins near the Delaware state line and extends downstream another 50 miles into the Delaware Bay. Finally, the lower 30 miles of the estuary, known as Delaware Bay, encompass a high-salinity zone heavily influenced by the Atlantic Ocean. Within this broad template, as in many estuaries, the highly variable freshwater inputs from the mainstem river, tributary streams, stormwater and discharges result in periodic salinity regime shifts, with major floods driving freshwater conditions far downstream into the normally brackish regions of the estuary, and protracted droughts allowing saltwater intrusion far upstream. For example, the historic 1960s drought led to brackish water conditions reaching the Ben Franklin Bridge between Camden and Philadelphia (River Mile 100)[4] just 10 miles from a drinking water intake for the City of Philadelphia.

Overlain on these natural transitions, and on the diversity of ecological communities adapted to these habitats, are decades of human abuses and water quality impacts to the Delaware Estuary. Historic and ongoing toxic chemical releases have required health advisories against eating fish caught in these estuarine waters. Raw sewage overflows drive pathogens and indicator bacteria numbers above criteria and impair recreational uses for portions of the urban corridor. Nutrient concentrations have climbed five-fold above historic levels, with the full consequences poorly studied (Jaworski et al., 1997). Channelization, dredging, and channel deepening have damaged or removed natural habitats and have brought saltwater intrusion further up the estuary (DiLorenzo et al., 1993; Philadelphia Regional Port Authority, 2020). Increasing salinization of freshwater inputs have likewise resulted in increased dissolved salts in the freshwater portions of the estuary, threatening the viability of drinking water intakes in the freshwater zones (DRBC, 2016).

Overshadowing and compounding these multifaceted impacts to the Delaware Estuary has been the past and ongoing problem with dissolved oxygen (D.O.). Hypoxia has long been recognized as both the most acute threat to life in the estuary and, fortunately, among the most tractable problems to solve. Hypoxic conditions (i.e., stressfully low dissolved oxygen levels) were first thoroughly documented over 100 years ago by the City of Philadelphia when surveys of summer conditions showed oxygen concentrations regularly below 2 mg/L (Philadelphia 1914). Dissolved oxygen regimes further

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[4] Positions along the Delaware River are measured in River Miles (RM) upstream from the Atlantic Ocean. See official delineation and positions on DRBCs website at https://www.state.nj.us/drbc/basin/river/.

deteriorated in subsequent decades, with the worst conditions documented during the 1940s, 1950s, and 1960s (Kiry, 1974; Sharp, 2010). Continuous U.S. Geological Survey (USGS) measurements beginning in the 1960s at Chester (RM 83) and the Ben Franklin Bridge (RM 100) then provided the grim details of the problem: anoxic conditions would commence each year in late spring, persist through the entire summer, and linger as late as November or December in the fall (USGS-NWIS, 2020).[5] Collaborative monitoring initiated in the 1960s by the State of Delaware and the Delaware River Basin Commission (known as the "Boat Run" survey) would further document the spatial extent of the dissolved oxygen problems: hypoxic conditions beginning near the water quality zone boundary at RM 108 and extending downstream below Wilmington, Delaware, with the worst anoxic and severe hypoxic conditions spanning a 25 mile reach from near RM 100 (Ben Franklin Bridge) to RM 75 near Wilmington, Delaware (Figures 1 & 2). Thus, anoxic and hypoxic conditions covered one-third of the estuary (45 miles) and persisted for up to five months each year across at least four decades beginning around World War II. These hypoxic conditions eliminated aquatic life from large sections of the tidal estuary, obstructed migratory fish passage, and further impaired the ecosystems in the areas where oxygen was depressed but not entirely eliminated.

The first effective efforts to curtail the gross pollution of the estuary and improve dissolved oxygen began in the 1950s with a federal effort that became the Delaware Estuary Comprehensive Study coordinated by the Federal Water Pollution Control Agency (Albert, 1988). With the creation of a new federal-state compact agency in 1961 (the DRBC[6]), and with passage of Federal Water Pollution Control Act (FWPCA) revisions in 1965 opening the door for water quality standards that crossed state lines, the stage was set for an experiment in ecosystem restoration for the central portion of the Delaware Estuary. Following contentious debate about the costs and aspirations for restoration, a compromise position was reached in 1967 by the four governors of the Basin states and the federal representative to the DRBC (FWPCA, 1966; Wright & Porges, 1971). In essence, the compromise set oxygen standards that would address the oxygen block just enough to allow migratory fish to pass around Philadelphia (both on their upstream journey as spawning adults and their downstream journey as young juvenile fish) and to further allow other resident fish and aquatic life to survive as adults. This compromise legal standard would not, however, restore oxygen levels high enough to allow broad-based use of the impacted areas in the estuary for spawning and rearing by fish and other sensitive aquatic species.

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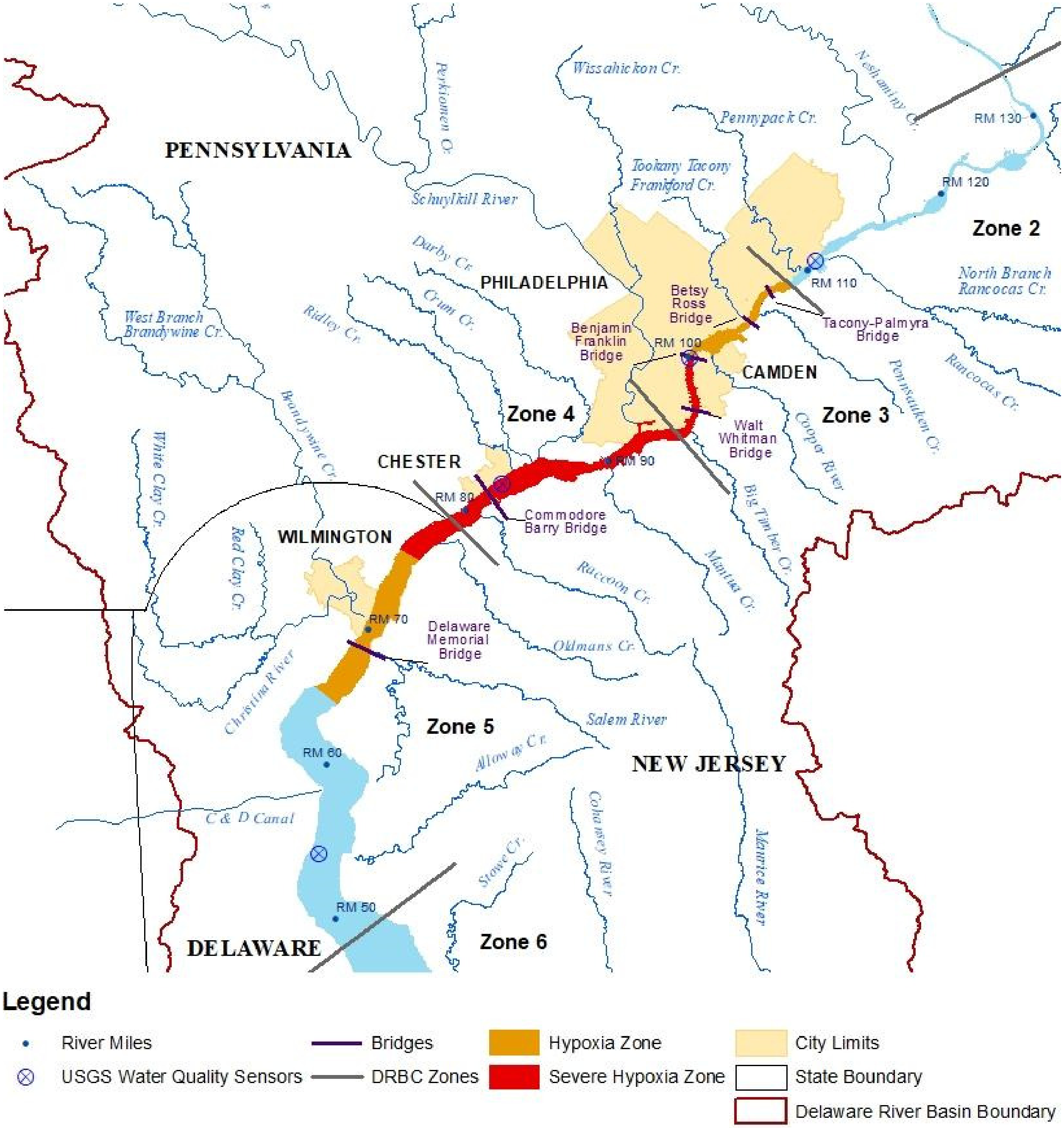
[5] Dissolved oxygen typically reaches its lowest values in summer during warmer temperatures simply because warm water can dissolve less oxygen than cold water. As a result, any depression in natural dissolved oxygen concentrations can lead to critically low levels for biological organisms during summer when dissolved oxygen concentrations are already at their naturally lowest values during the year. Climate change and global increases in temperatures further threaten to exacerbate these problems, although this report does not attempt to further evaluate the complexities of climate change on the Delaware Estuary.

[6] The Delaware River Basin Commission (DRBC) was created in 1961 as the four basin states (Delaware, New Jersey, New York, and Pennsylvania) and the federal government relinquished their own authority to a powerful new compact agency with jurisdiction over water supply and water quality (among other powers) within the watershed (basin) of the Delaware River.

Figure 1. Spatial Extent of Historic Dissolved Oxygen Problems in the Delaware Estuary (ca. 1965)



Note. Depression in dissolved oxygen is separated into areas of Hypoxia (< 5 mg/L) and Severe Hypoxia (<2 mg/L) based on typical minima and daily average conditions from the mid-1960s. Spatial data for creeks and rivers is adapted from Delaware River Basin Commission [DRBC] (2004a); Delaware River Basin boundary from DRBC (2004b); municipal boundaries from Chester County, Pennsylvania (2018); dissolved oxygen data from Federal Water Pollution Control Administration [FWPCA] (1966), DRBC (1968), Sharp (2010), USGS-NWIS (2020).

Translated into the language of water quality standards, the goal was set at "maintenance only" for aquatic life, rather than for the complete protection of "maintenance and propagation."[7] These 1967 water quality standards began the turnaround for the Delaware Estuary. The subsequent historic revisions to the FWPCA in 1972 (now referred to as the first "Clean Water Act") further accelerated the restoration through funding, enforcement, and heighted legal requirements for compliance from pollution dischargers. But in the final analysis, the standards set and actions taken could not, and did not, restore oxygen levels high enough to fully support and sustain healthy water quality and aquatic life.

Certain details from the initial 1967 compromise require further explanation as they establish the context for contemporary dissolved oxygen problems in the estuary, and the basis for further restoration. First, the four basin states and the federal government acted through the powers of the new interstate agency, the DRBC, with the promulgation of water quality standards in 1967 and the subsequent allocation of "wasteloads" to meet those standards in 1968 (essentially a pollution budget).

Second, different goals ("uses to be protected") were established by DRBC for different zones of the tidal estuary. Upstream near Trenton, the full "maintenance and propagation" goal for fish and aquatic life was established for Zone 2 (Figure 2). Similarly, below the hypoxic urban corridor, the full "maintenance and propagation" was established for Zone 6 (Delaware Bay) and the lower portion of Zone 5 below RM 70 near the mouth of the Christina River. For all of Zones 3 and 4, and for the upper portion of Zone 5 (RM 70 to RM 78.8), "maintenance of fish and other aquatic life" was the reduced target for these urban zones of the river (albeit an ambitious goal given the historic anoxia and lack of aquatic life). These compromise designations were in stark contrast to the 1972 goals outlined in the first Clean Water Act for all waters in the nation. In Section 101(a)(2), the Clean Water Act clearly states that "it is the national goal that wherever attainable, an interim goal of water quality which provides for the protection ***and propagation*** of fish, shellfish, and wildlife and provides for recreation in and on the water be achieved by July 1, 1983" (emphasis added).[8] Unfortunately, the goal for the Delaware Estuary has never been upgraded to the full aquatic life use articulated in the Clean Water Act, and even in the year 2020 the goal for Zones 3, 4, and upper Zone 5 remains "maintenance only" despite having a scientifically demonstrated higher existing use.

The third important detail of the 1967 compromise lies in the D.O. targets themselves. To support the different goals or "uses" in the different portions of the estuary, the 1967 standards adopted by DRBC (and still unchanged in 2020) set different acceptable levels for dissolved oxygen in the different zones of the estuary (Figure 2).

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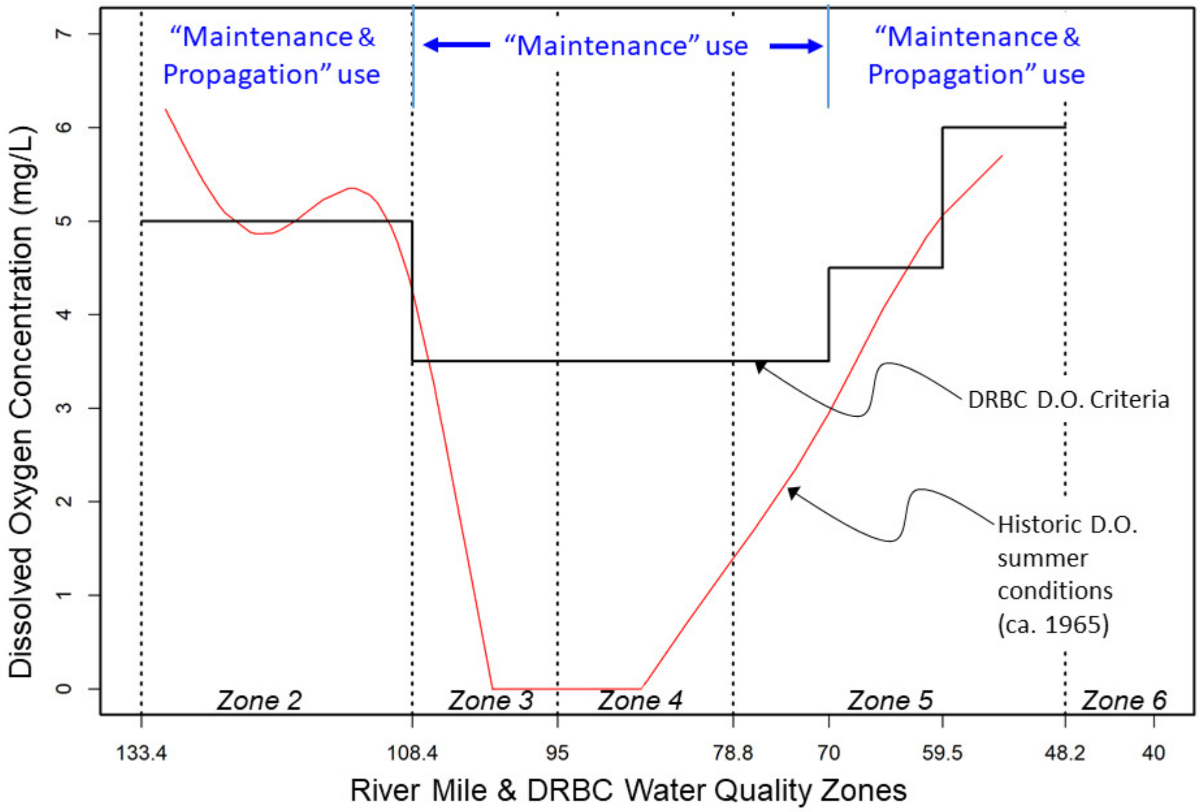
[7] "Propagation" is used in water quality standards, including the Clean Water Act, to denote the spawning and early life stages that are more sensitive to many environmental stressors. For instance, the State of Delaware's water quality standards define propagation as "reproduction of fish, aquatic life and wildlife within their natural environment" (7 De. Code § 7401).

[8] Federal Water Pollution Control Act (33 U.S.C. 1251 et seq., aka "Clean Water Act"), Section 101(a)(2).

Figure 2. Water Quality Standards & Historic Dissolved Oxygen Conditions for the Tidal Delaware River

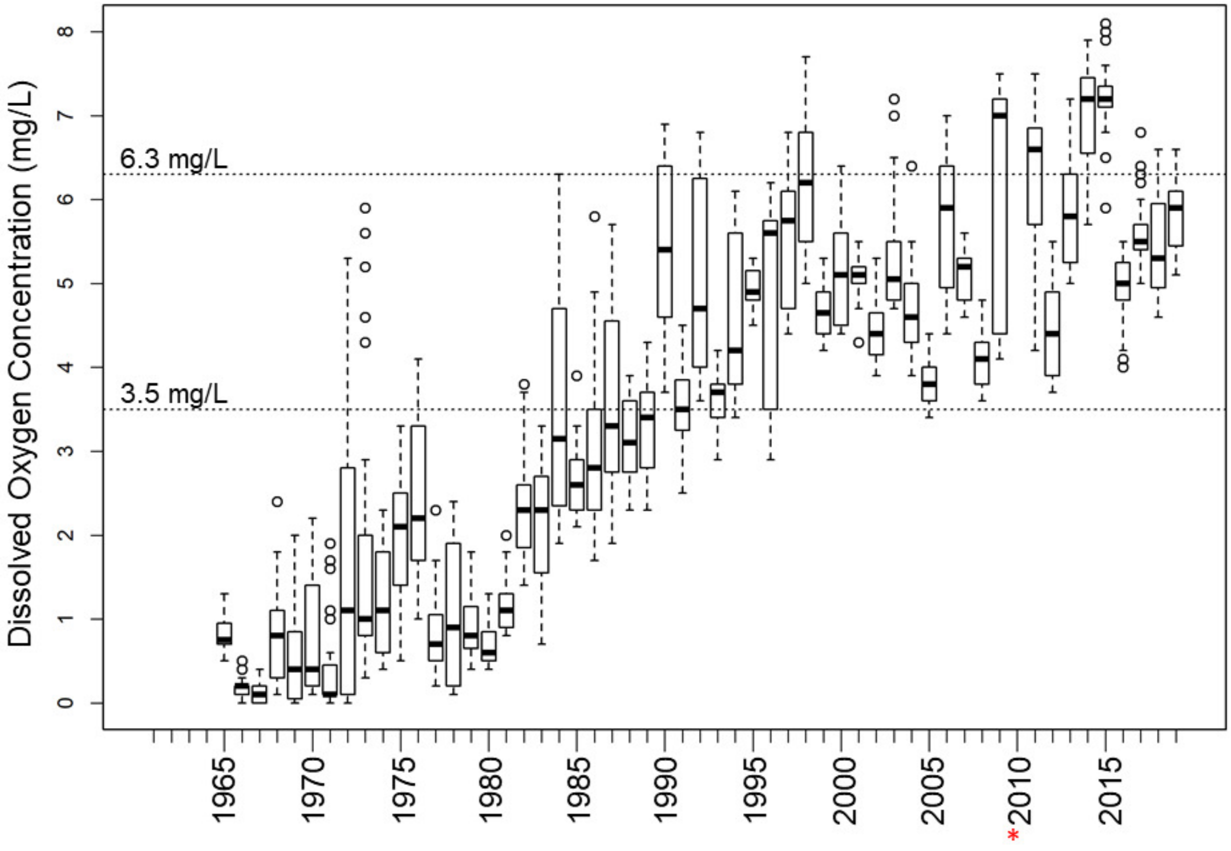


Note. Water quality standards summarized from DRBC (2013); "Uses to be Protected" shown in blue at the top of the graph; numeric dissolved oxygen criteria ("Stream Quality Objectives" as 24-hour daily average) shown as solid black line; water quality management zones separated by dotted lines. Historic dissolved oxygen conditions based on summertime minima and daily average conditions from the mid-1960s; data sources from FWPCA (1966), DRBC (1968), Wright & Porges (1971), Sharp (2010), USGS-NWIS (2020).

Most importantly, for the maintenance-only zones, the daily average D.O. standard was set to a modest 3.5 mg/L, substantially below the recognized requirements for sensitive aquatic species at that time (e.g., FWPCA 1968, aka "the Green Book"). Again, relative to the D.O. concentrations at or near 0 mg/L each spring, summer, and fall, the 3.5 mg/L goal was significant and meaningful. But the final decision in 1967 was not to try to restore the full ecology of the estuary, but to incrementally bring resident and migratory fish back to the system, and revisit the goals again at a later date (Wright and Porges, 1971).

Finally, the 1967 standards focused on carbon rather than nitrogen sources for restoring dissolved oxygen, both because carbon sources were the larger fraction and because they would be easier to treat and control. In the 1960s, carbon and nitrogen fractions dominated the ongoing discharge of biochemical oxygen demand (BOD; see Key Abbreviations & Terms) into the river, with the carbon fraction (CBOD) the larger of the two (FWPCA, 1966). For the year 1964, the CBOD daily load was estimated at 1,000,000 lbs/day (approximately three-fifths the point source load) compared to the nitrogen fraction (NBOD) at 600,000 lbs/day (two-fifths the point source load).[9] Further, the carbon fraction was seen as the easier fraction to treat, in part because it was the faster component of the demand and was even referred to historically as "first stage oxygen demand" or FSOD (Wright & Porges, 1971). The 1968 wasteload allocation thus focused exclusively on targets for CBOD within the estuary, with each point source facility given both daily load allocations and percent removal requirements for their overall carbon component of the BOD load.

Figure 3. Dissolved Oxygen Recovery at the Ben Franklin Bridge (RM 100) from 1965-2019 (July data)



Note. Graph depicts box-and-whisker plots of full data distribution for 24-hour daily average dissolved oxygen readings (data from USGS-NWIS 2020) in the month of July at the USGS Ben Franklin Bridge station (#01467200) from 1965 thru 2019 (*except no data presented for 2010; sensor problems precluded accurate readings during a period of low dissolved oxygen in July-2010). Current 3.5 mg/L standard (DRBC, 2013) and recommended 6.3 mg/L protective value (Academy of Natural Science of Drexel Univ, 2018) shown with horizontal dotted lines.

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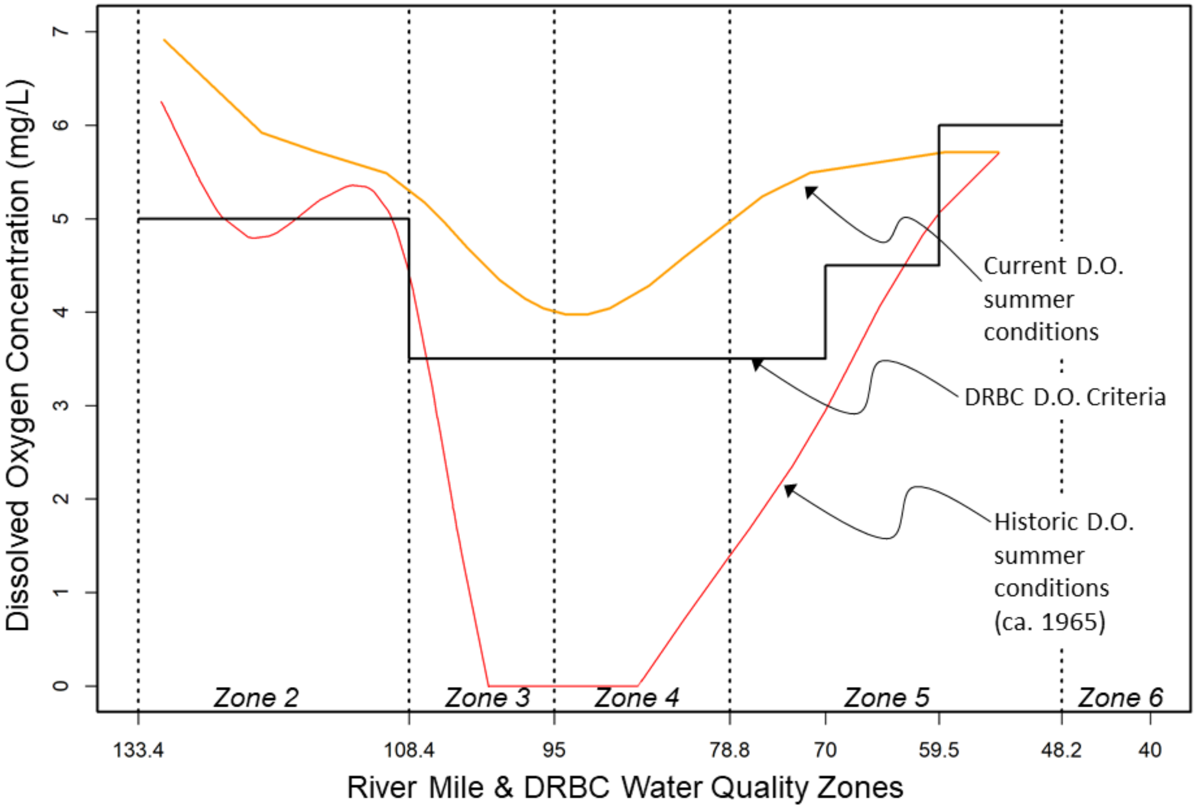
[9] See McGuire (2019), an online popular science article that provides an illustrated explanation of the sources of CBOD and NBOD in the Delaware River; available at https://delawarecurrents.org/2019/08/18/clean-water-mind-your-pees-and-carbons/.

Together, then, the 1967 standards and the 1968 wasteload allocation established the requisite policies for significant improvements of dissolved oxygen and the elimination of fully anoxic conditions in the Delaware Estuary. The recovery, of course, would not occur overnight. With the many benefits of the 1972 Clean Water Act bolstering the effort, important improvements began to be realized for the Delaware River in the 1980s (Figure 3). By the 1990s, anoxic conditions had been largely eliminated and for the first-time dissolved oxygen regularly exceeded the 3.5 mg/L target established in 1967 for all areas of the estuary.

Since the 1990s, however, dissolved oxygen improvements have stalled (Figure 3). And while dissolved oxygen has typically exceeded the 3.5 mg/L compromise established in 1967, no general trend of improvements is discernible since 2000. While during individual summers D.O. has remained above 5.0 mg/L for the entire summer (e.g., 2014 which is likely the best summer dissolved oxygen levels experienced in over 100 years), D.O. regularly falls below 4 mg/L during other summers (e.g., 2008, 2010, 2012, 2020).

Figure 4. Historic vs Contemporary Summertime Dissolved Oxygen Sag in the Delaware Estuary



Note. Historic dissolved oxygen conditions (solid red line) based on summertime minima and daily average conditions from the mid-1960s; current dissolved oxygen conditions (solid orange line) based on the “Low” statistic for summertime D.O. concentrations (i.e., 10th percentile of daily average D.O. concentrations, June-July-August); data sources from FWPCA (1966), DRBC (1968), Wright & Porges (1971), Sharp (2010), Philadelphia Water Department [PWD] (2016), DRBC (2018a), USGS-NWIS (2020). See Figure 2 for additional details.

As shown in Figure 4, the historic anoxic conditions for Zones 3 and 4 have modulated to a dissolved oxygen “sag” that depresses oxygen levels in the urban corridor of the estuary. Furthermore, as highlighted by the DRBC-commissioned study in 2018, oxygen needs for fish such as Atlantic sturgeon are as high as 6.3 mg/L, highlighting the inadequacy of the antiquated 3.5 mg/L standard for protecting all species of aquatic life in the Delaware Estuary (Academy of Natural Sciences of Drexel University, 2018).

Policy Context: Potential for Further Dissolved Oxygen Restoration

While significant progress has been made to eliminate anoxia and improve dissolved oxygen concentrations in the tidal Delaware Estuary, further improvements are readily achievable and needed to fully support aquatic life. First highlighted during the 1960s efforts, the nitrogen-based fraction of the BOD load (NBOD) has never been regulated for the Delaware Estuary. Incredibly for the 21st century, end-of-pipe requirements for point source dischargers to the tidal Delaware River generally remain at the antiquated level of 35 mg/L,[10] similar to the typical influent concentrations for municipal wastewater facilities (Atlas et al., 1998). While some reductions in total NBOD loading have occurred since the 1960s, the most recent comprehensive evaluation estimated that a depression of D.O. up to 2 mg/L occurred in the urban corridor from NBOD alone (Hydroqual, 1998). The reduction or removal of NBOD through a process called nitrification, moreover, is conventional technology already incorporated into many of the smaller facilities discharging to the tidal estuary as part of the upgrades developed since 1967 (e.g., Kent County, City of Burlington, Mt Holly, Tinicum Township; PWD, 2016; E.L. Silldorff unpublished data). The costs for building the infrastructure and the annual operation to maintain nitrification, however, are high enough that the largest municipal dischargers to the estuary (e.g., Philadelphia’s three wastewater treatment plants (WWTPs), Camden County, Wilmington, Gloucester County) have generally postponed implementation of nitrification. These, and a handful of other facilities, have instead continued to allow the nitrification process to be completed in the estuary, utilizing significant quantities of the estuary’s dissolved oxygen rather than oxygen supplied to the treatment plants themselves, and resulting in a D.O. sag and persistent depression in D.O. conditions for the urban corridor of the estuary (Hydroqual, 1998; DRBC, 2018b; see Figure 4).

Increased realization of both the opportunity for more complete restoration of dissolved oxygen, and recognition of the injustice toward human communities and the estuarine ecosystem embodied in the failure to act, have supported increasing momentum to complete the restoration of dissolved oxygen for this estuary and to attain the full potential of this ecosystem (DRBC Resolution 2017-4). Yet as before, the public policy decisions to achieve this change have focused too narrowly on the financial costs of operating WWTPs while largely ignoring the ongoing costs to vulnerable communities, to society, and estuary life as a whole that are the consequence of a failure to act (e.g., DRBC, 2018c). For informed and forward-thinking decisions to be possible, the “benefits” side of the restoration of dissolved oxygen—

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[10] See DRBC’s “Effluent Quality Requirements” Section 4.30.5 of Water Quality Regulations (DRBC, 2013).

benefits that include the amelioration of those societal costs—must be fully understood, enumerated, and articulated in dollars-and-cents terms.

Given the relatively straightforward path for restoring dissolved oxygen and bringing the tidal Delaware River into greater compliance with the Clean Water Act, it is clear that other societal dimensions of the issue are controlling the decision-making process. In particular, the discharger community in the Philadelphia-Camden-Wilmington region is relatively well-organized and well-represented on key policy committees. The individual facilities and the broader regulated community are well-positioned to articulate the costs in terms of facility upgrades, maintenance, and higher rates and fees. The result is an over-emphasis on the costs of plant upgrades (borne by dischargers and ratepayers) and an under-emphasis, or even a failure, to consider other key costs and benefits: the full array of community costs caused by continuing depressed oxygen levels; and, the benefits of restoration including the distribution of those community-costs and benefits among the region's more vulnerable communities.

That under-emphasis persists in part because the benefits are only vaguely understood and often poorly articulated. The inclusion of benefits in this broader conversation is of particular importance for and to the communities that have little representation in the processes that will decide how, and how quickly, the Delaware Estuary is restored. Through this project, we address this imbalance by developing an appropriate, rigorous understanding of the benefits of dissolved oxygen restoration in the Delaware River estuary and equipping a broader community to promote, support, and participate in the restoration as well as the benefits it will produce.

Environmental Justice Considerations

As mentioned above, among the voices missing from the policy debate are those of disadvantaged human communities who, for so long, have borne the burden of the consequences of inaction. These include ill health, less access to clean, pleasant areas for recreation and relaxation, depressed property values, and limited economic opportunity resulting from businesses choosing cleaner, healthier areas in which to locate (Hurdle, 2018; Rourke, 2020; Foy, 2012).

Within the estuary, pockets of poverty appear to be more prevalent near the most degraded portions of the Delaware River, including in the cities of Camden, Philadelphia, Chester, and Wilmington. (See Figure 5).[11] These four cities also contain some of the region's largest concentrations of minority populations as well as lower household and per capita personal income levels compared to metropolitan[12] and state averages (Figure 6 & Figure 7).

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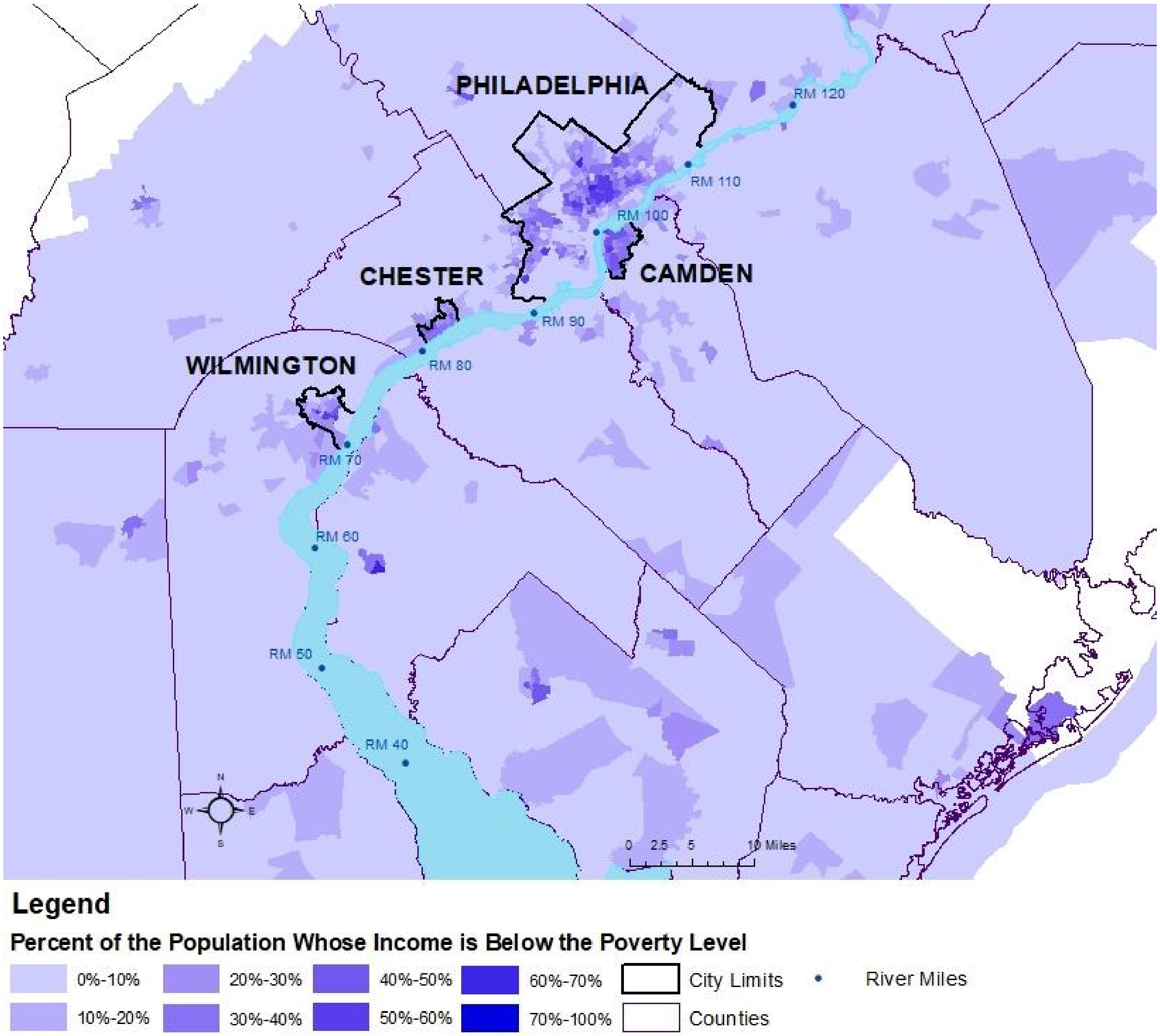
[11] Similar environmental justice maps can be interactively displayed using the U.S. EPA's Environmental Justice Screening and Mapping Tool. https://ejscreen.epa.gov/mapper/.

[12] "Metropolitan" areas are used to compare city averages to other metropolitan (non-rural) counties in the respective state. The Office of Management and Budget defines metropolitan areas as "broad labor-market areas that include (U.S. Department of Agriculture, 2019):

> 1) Central counties with one or more urbanized areas; urbanized areas (described in the next section) are densely-settled urban entities with 50,000 or more people. (Continued on page 19).

Figure 5. Percentage of Families and People Whose Income in the Past 12 Months is Below the Poverty Level, 2013-2017 5-Year American Community Survey (ACS)



Note. Data is displayed on the census tract level. The poverty data is from the U.S. Census Bureau (2020a); county boundaries from U.S. Census Bureau (2016); municipal boundaries from Chester County, Pennsylvania (2018).

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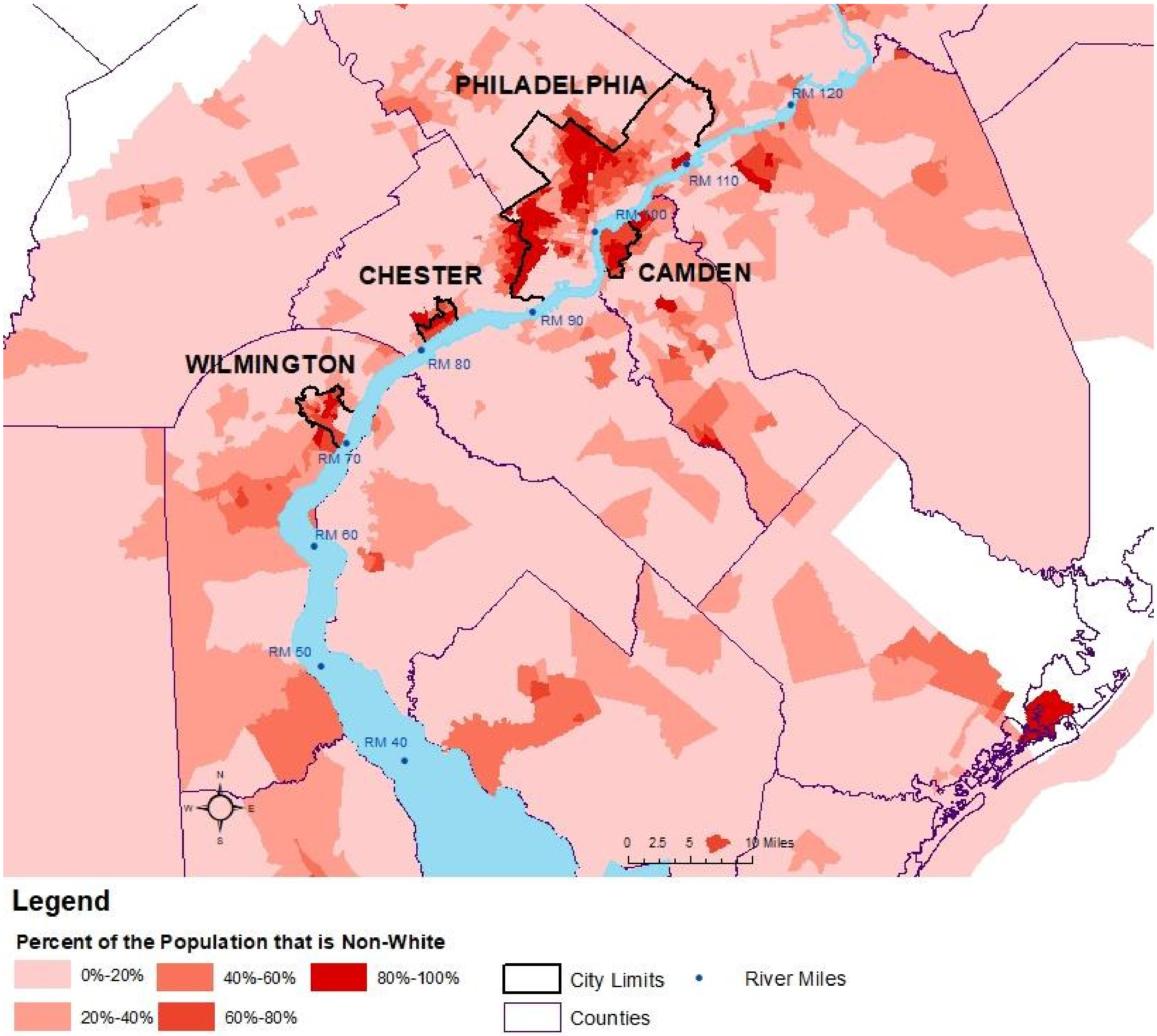
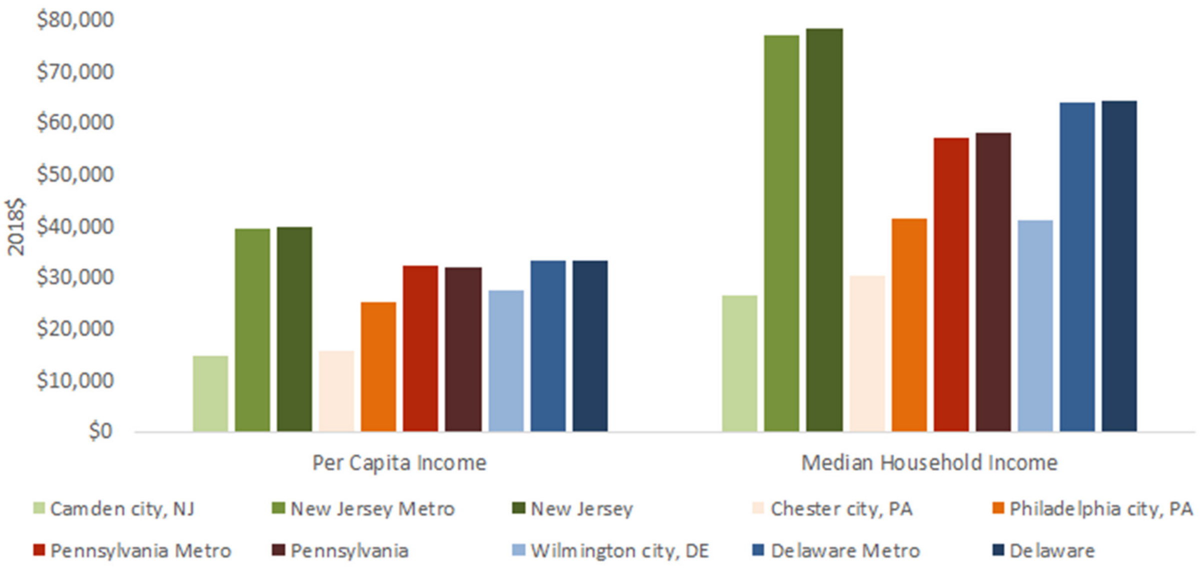
(2) Outlying counties that are economically tied to the core counties as measured by labor-force commuting. Outlying counties are included if 25% of workers living in the county commute to the central counties, or if 25% of the employment in the county consists of workers coming out from the central counties—the so-called "reverse" commuting pattern.

Figure 6. Percent of the Population that is Non-White, 2013-2017 5-Year ACS



Note. Data is displayed on the census tract level. The demographic data is from the U.S. Census Bureau (2020b); County boundaries from U.S. Census Bureau (2016); Municipal boundaries from Chester County, Pennsylvania (2018).

Figure 7. Income in Delaware River Cities, with Metropolitan and State Figures for Comparison (2018$)



Note. Income data (adjusted to 2018$) is from the Headwaters Economics Economic Profile System which consolidated data from the U.S. Department of Commerce et al. (2018).

These patterns suggest that lower water quality is experienced disproportionately by communities of color, economically distressed and/or otherwise vulnerable populations—indicating that residents in these cities may face environmental injustices. Environmental justice, as defined by the U.S. Environmental Protection Agency (EPA), is the “fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation and enforcement of environmental laws, regulations and policies” (U.S. Environmental Protection Agency [U.S. EPA], 2015).

- Fair treatment means that no person, or groups of people, should bear a disproportionate amount of environmental harm.
- Meaningful involvement means that people should have opportunities to participate in decisions about activities that may affect their environment and/or health; Contributions made by the public can influence the regulatory agency’s decision; Community concerns are considered in decision-making processes; and Decision makers seek out and facilitate the involvement of those affected.

Our research quantifies the benefits of dissolved oxygen restoration in economic terms for the estuary and, where possible, for areas within the region. This leavens the public policy debate with a more complete picture of the economic value of taking action (or the economic consequences of continuing to fail to take action).

Method for Analysis - Ecosystem Services Framework

The main objective of this analysis is to estimate the magnitude and distribution of economic effects of improved dissolved oxygen in the Delaware Estuary through an ecosystem services assessment framework. This framework provides a systematic way of understanding the relationships between ecosystems and human well-being within a defined landscape. In this framework, the causal and value chain from policy choices/management actions, to ecosystem function, to ecosystem service supply, to societal (including economic) benefit is explicit. Moreover, because the spatial extent of relationships between ecosystem and human "endpoints" is hardwired into our definition, we can map where the benefits accrue and consider whether they provide any particular advantage to vulnerable communities.

What are Ecosystem Services?

First coined in the 1960s, the term "ecosystem services" is not at all novel. Nor is the underlying idea that the well-being of people originates, ultimately, in the well-being of the natural environment. Indeed, it is not an overstatement to say that ecosystem services are the way that humans have always experienced our relationship with the non-human world.

We adopt a definition of ecosystem services as "the effects on human well-being of the flow of benefits from an ecosystem endpoint to a human endpoint at a given extent of space and time" (Johnson et al., 2010).

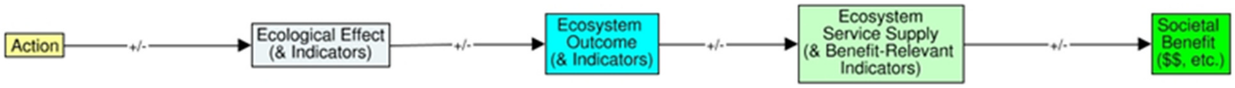
We implement this ecosystem framework through three elements in this analysis:

- Evaluating Means-Ends Diagrams Using the National Ecosystem Service Partnership Guidebook
- Spatial Analysis Connecting Sources, Sinks, and Benefit Areas
- Estimating Key-Ecological and Economic Outcomes

Element One: Evaluating Means-Ends Diagrams Using the National Ecosystem Service Partnership Guidebook

The first element lays out the most important pathways by which our predefined stressor connects to biophysical and economic quantities. Once pathways between the action and ecosystem services are established, we can measure how changes in ecosystem service provision in the estuary translates into socioeconomic benefits. We use the technique established by the National Ecosystem Service Partnership Guidebook (NESP) known as Means-Ends Diagramming to link changes in management to outcomes, including the market and non-market benefits conveyed by commercial and recreational uses, and property values (Figure 8).

Figure 8. Means-Ends Diagram Framework



Element Two: Spatial Analysis Connecting Sources, Sinks, and Benefit Areas

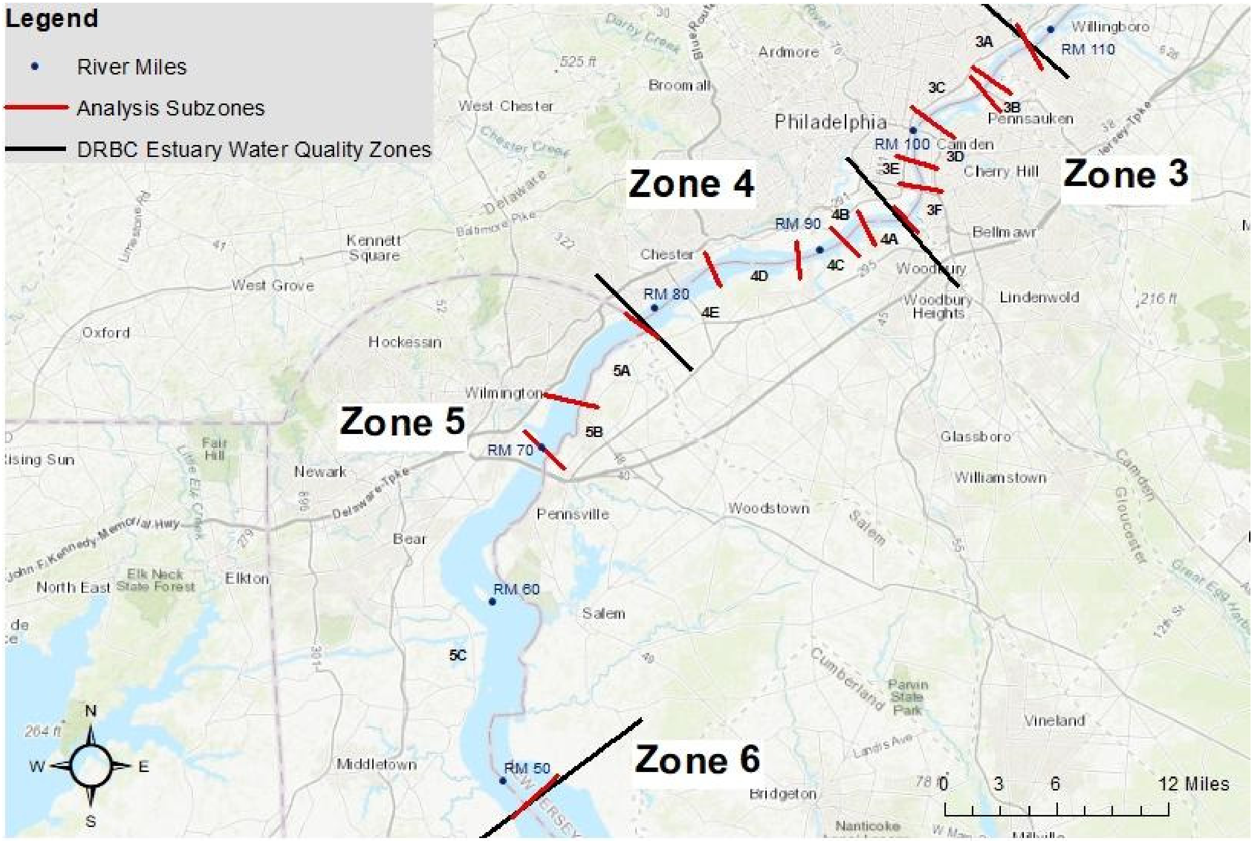
After identifying key ecosystem services and societal benefits or outputs in the estuary using Means-Ends Diagramming (See Figure 10), we connect actions and ecosystem processes to geographically-specific areas where ecological and/or economic outcomes could occur. The differences in the biophysical characteristics within the estuary translate into different ecological impacts and different economic outcomes—even for the same ecosystem service—depending on where the effects occur in the estuary.

Study Region Zones and Subzones

As described above, the contemporary depression of dissolved oxygen extends across the urban corridor of the estuary, from Philadelphia and Camden down to Wilmington. In these areas, the Clean Water Act's 101(a)(2) goals for "the protection and propagation of fish, shellfish, and wildlife" have never been designated and instead remain at the 1967 "maintenance only" designations. As a result, the dissolved oxygen standard likewise remains at the antiquated and non-protective value of 3.5 mg/L as a 24-hour average beginning at River Mile 108.4 and extending downstream to River Mile 70.0 (Figure 2; Zone 3, 4, and 5). To recognize the influence of the dissolved oxygen sag on downstream receiving waters, the dissolved oxygen standard is only slightly elevated to 4.5 mg/L from River Mile 70.0 downstream to River Mile 59.5 within Zone 5, as well.

Areas of both lower dissolved oxygen conditions and lower water quality standards in Zones 3, 4, and 5 are the focus of our analysis. Yet because these DRBC zones extend across extensive lengths of the estuary (13 miles, 16 miles, and 31 miles, respectively) in an area where substantial changes in dissolved oxygen conditions also occur within each of these zones (Figure 4), the forecast change to dissolved oxygen and to ecological conditions is heterogeneous within these larger zones. In order to create more homogenous areas of the river for modeling, where D.O. conditions and predictions as well as ecological changes would be relatively stable across the length of a river section, the three DRBC zones were divided into roughly three-mile-long subzones (ranging from one to six miles) as well as one relatively long subzone (5C, below Wilmington) where current and predicted dissolved oxygen conditions are relatively stable (Figure 4). Final boundaries for these subzones were further modified to tie into census tract boundaries, allowing for spatial analysis of relevant economic benefits. Specifically, water quality and ecological changes adjacent to distinct political and socioeconomic boundaries were identified with modeling and predictions centered on the midpoint of each subzone (Figure 9).

Figure 9. DRBC Water Quality Zones and Study Region Subzones



Note. Boundaries for the DRBC zones are from the DRBC (2020); sources for the basemap are from Esri, HERE, Garmin, Intermap, Increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster N L, Ordnance Survey, ESRI Japan, METI, Esri China (Hong Kong), © OpenStreetMap contributors, and the GIS User Community.

Distribution of Economic Benefits

Our analysis of the economic distribution of benefits focuses on the population residing within two miles of the Delaware River and the lower tidal Schuylkill River, with a specific focus on the cities of Chester, Camden, Wilmington, and Philadelphia.[13] Tidal creeks typically extend their tidal influence well beyond two miles from their confluence with the river, and the communities living near the river and its tributaries are affected by water quality and overall access to these waters at least two miles inland from the waterway. Furthermore, residents within two miles may gain more from water quality improvements, considering this population may be more likely to engage in water-based activities.

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[13] The lower tidal Schuylkill River was included in the analysis since its dissolved oxygen regime is strongly influenced by and mirrors the changes in the tidal Delaware River, particularly in the lower two miles of the tidal river near its confluence with the Delaware River.

Element Three: Estimate Key Ecological and Economic Outcomes

To translate ecosystem values—generally biophysical quantities estimated using the methods described above—into ecosystem service supplies and associated monetary value, we use the "benefit transfer method" (BTM). BTM applies per-unit values (such as the avoided cost of drinking water treatment per 1,000 gallons, or the fee for a day's guided fishing) or more complex functions[14] from multiple studies of "source" areas—areas similar in relevant ways—to a "policy" area. In our case, the policy area is the Delaware Estuary.

The Economic Value of Restoring Dissolved Oxygen in the Delaware Estuary

As funders, developers, and other decision makers involved in the management of natural resources become more interested in the value of benefits we receive from nature, the need for a model to assess how decisions or policies change these benefits becomes increasingly urgent and essential. Ecosystem service conceptual models, like means-end diagramming, can help to simplify complex relationships between humans and the environment while providing a common framework for any place or intervention.

In the Delaware Estuary, this framework allows us to connect biophysical processes to economic outcomes. This creates a more complete picture of how improving dissolved oxygen can result in the greatest change in benefits to communities and the general public over space and time by quantifying the affected ecosystem services' values. Figure 10 lays out the means-end diagram pathways developed for this analysis and the full model web (including elements not modeled) can be found in Appendix C: Conceptual Model of Ecosystem Response to Changes in BOD Loading. It is important to note that the means-ends diagram captures a number of key pathways within the broader ecosystem response, but that some ecosystem responses could not be quantified in a manner that allowed for quantitative estimates of economic benefits. As a result, the quantified benefits are conservative estimates of both the total ecosystem benefits and the total economic benefits of the dissolved oxygen improvements.

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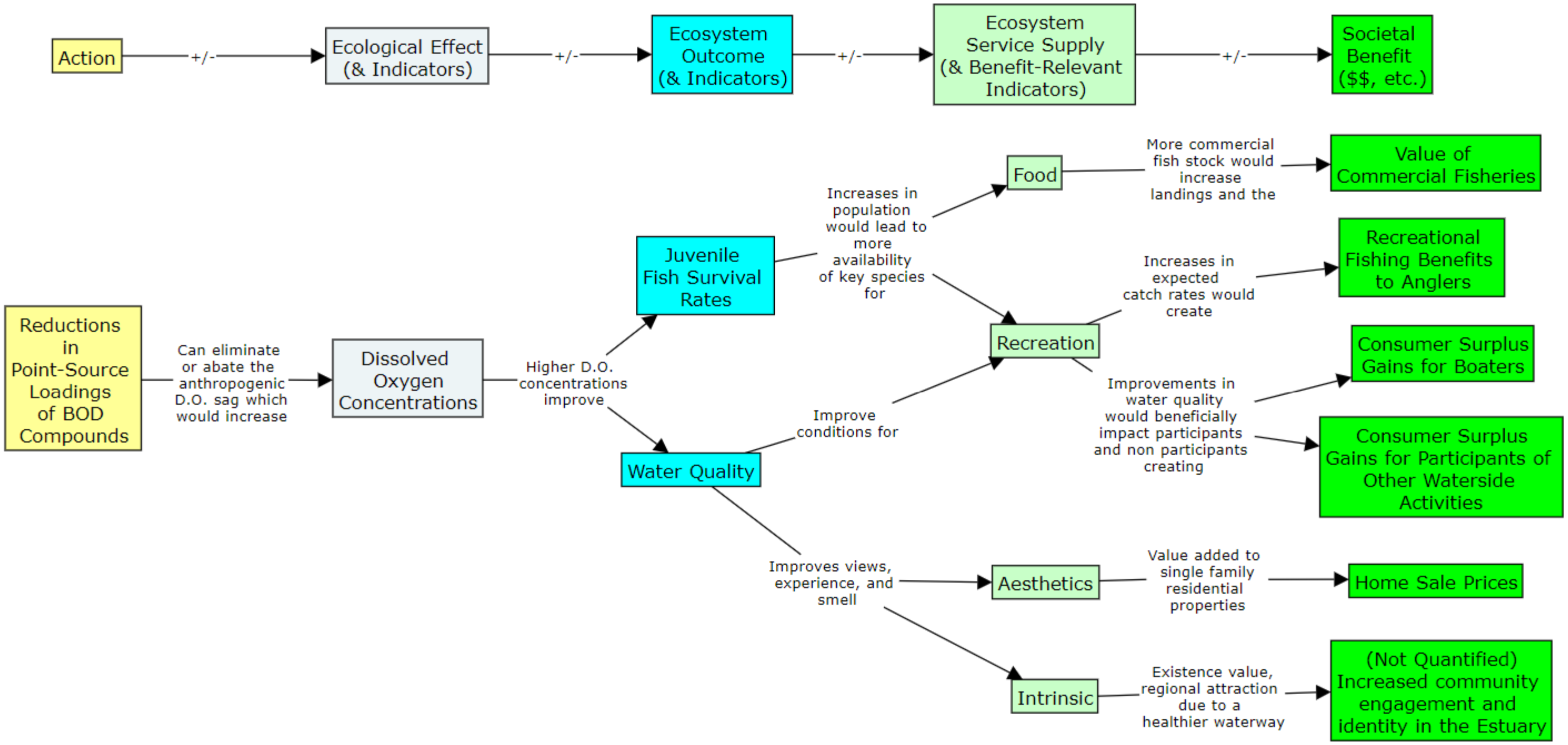
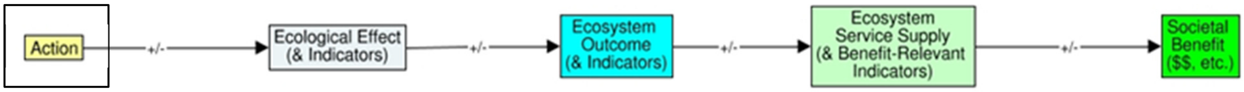
[14] The values and functions from the source studies arise from various ecosystem service valuation techniques, including the travel cost method for recreational value, and hedonic pricing for property value impacts. Passive use values come from studies using stated preference techniques, such as contingent valuation or choice experiments.

Figure 10. Means-Ends Diagram for Dissolved Oxygen Improvements in the Delaware Estuary



Actions

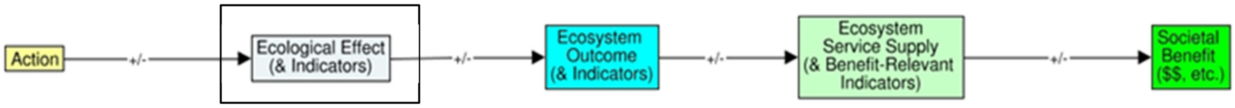


“Actions”, shown in the yellow box, are interventions, policy scenarios, etc., that can have both positive and negative effects when their implications cascade through the ecosystem. It is well-established that the contemporary dissolved oxygen sag in the Philadelphia-Camden-Chester reach of the Delaware Estuary is caused by anthropogenic loading of biochemical oxygen demand (BOD), primarily from point source wastewater facilities (Hydroqual, 1998; DRBC, 2018b; DRBC, 2019a). The anticipated “Actions” to restore dissolved oxygen are therefore not limited to any one policy or management action but refer collectively to the reductions in point-source loading of these BOD compounds, which are essentially a suite of microbial food sources, both organic and inorganic. As described earlier, the original improvements to dissolved oxygen seen from the 1960s to the 1990s arose from regulations and allocations of “carbon-based” fractions, or CBOD discharges, at point source facilities. By contrast, there have been no regulations that specifically target the “nitrogen-based” microbial food sources (NBOD), although some reductions to NBOD loading have been observed since the 1960s even in the absence of regulations. Without broad requirements and permit limits on NBOD for the estuary, the current dissolved oxygen sag is primarily driven by NBOD loading from point source facilities, with the most recent modeling suggesting dissolved oxygen is reduced between 1.5 mg/L and 2.0 mg/L by the NBOD loading from point sources alone (Hydroqual, 1998).

In the 1960s, simultaneous reductions to CBOD and NBOD loading were considered overly ambitious and difficult to achieve. Regulations, therefore, targeted the larger and easier-to-treat fraction of the BOD load, the CBOD fraction (Wright & Porges, 1971). However, over 50 years after those initial decisions, the treatment and reduction of both CBOD and NBOD are conventional technologies in wastewater facilities, and many of the smaller treatment plants in the Delaware Estuary have already incorporated NBOD reductions into their designs. Yet without requirements for NBOD reductions (or the associated ammonia discharge limits), several facilities have postponed implementation of nitrification (the conversion of NBOD and ammonia) or other similar NBOD treatment technologies. Of greatest importance for the dissolved oxygen sag, six of the seven largest municipal dischargers to the estuary have not incorporated nitrification or NBOD load reductions into their facilities’ designs (i.e., Camden County, Gloucester County, City of Wilmington, and the three Philadelphia plants; see DRBC 2018b). These six facilities typically discharge between 70% to over 90% of their total nitrogen as ammonia or NBOD compounds, and together these six facilities are estimated to discharge approximately 91% of the total NBOD point source load into the estuary (PWD 2016; DRBC, 2019a; E.L.Silldorff unpublished data). Moreover, these six facilities are all concentrated in the urban corridor of the estuary and essentially bracket the upper and lower bounds of the contemporary dissolved oxygen sag (DRBC, 2018b).

Again, the “Actions” identified in this analysis are more broadly defined as those that will increase the estuary’s dissolved oxygen and attenuate or eliminate the dissolved oxygen sag. The single most important and effective requirement will be the implementation of nitrification or other NBOD load reduction technologies at the six largest facilities dominating the current oxygen sag. Additional NBOD load reductions may likewise prove important at other facilities that currently have little or no NBOD treatment. Finally, the CBOD loading from the suite of point source facilities is still a significant contribution to the overall BOD load in the estuary and individual facilities may need, or may choose, to attain their BOD load reductions by also improving their treatment for CBOD and thus reducing their CBOD loading. In summary, the BOD point source loads cause the contemporary depression of dissolved oxygen to ecologically dangerous levels; reduction of this BOD loading is the action that will reduce or eliminate the dissolved oxygen sag, primarily through the reduction in the NBOD loads.

Ecological Effects (& Indicators)

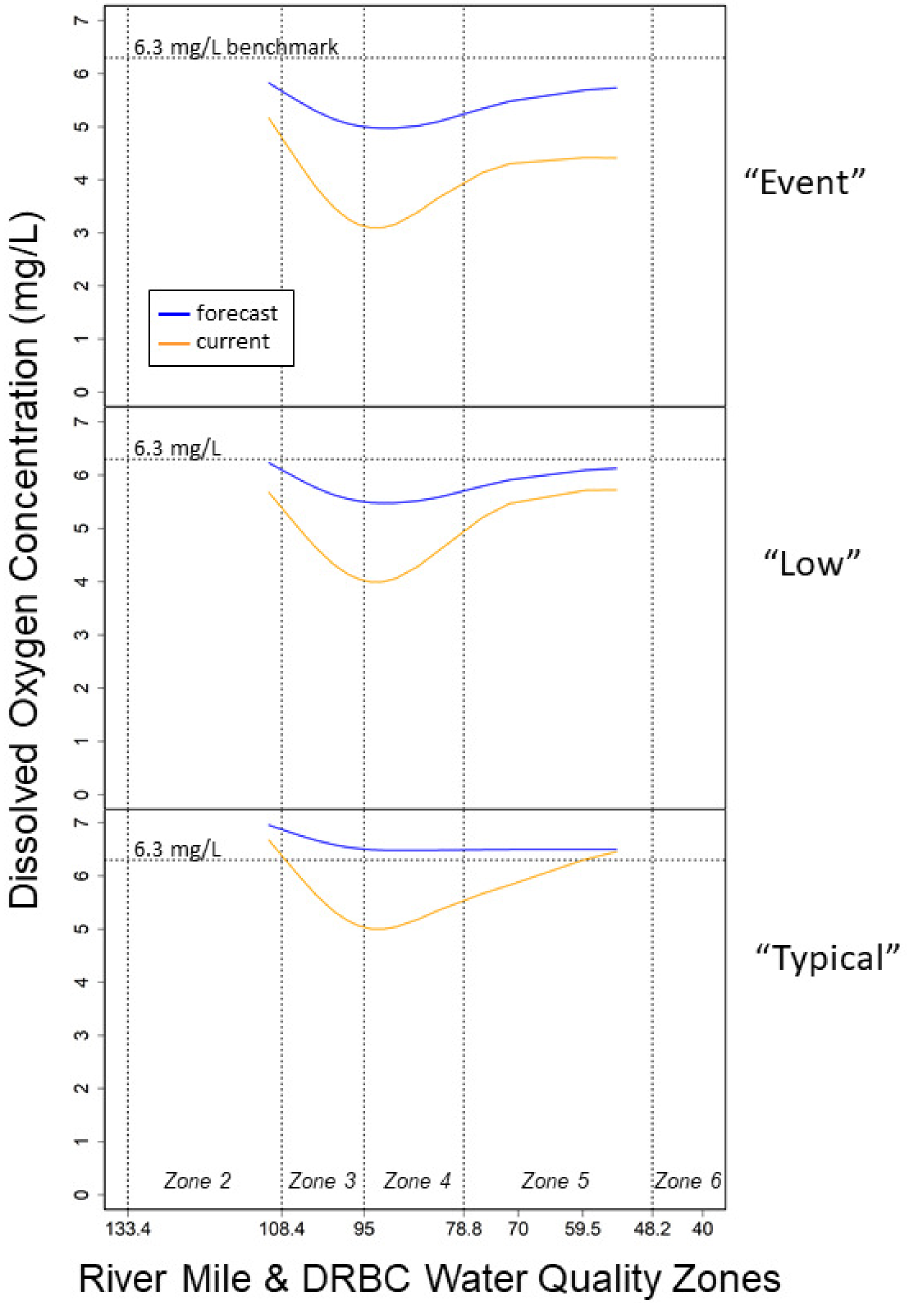


“Ecological effects”, the grey box, represents direct impacts to the ecosystem that might be expected from the management actions. The most important direct effect from BOD load reductions will be improved summertime dissolved oxygen conditions in the urban portion of the Delaware Estuary (i.e., beginning in Camden and Philadelphia and extending down through Chester and toward Wilmington). This is the intended outcome of the load reductions, and such BOD load reductions can and will improve dissolved oxygen conditions (e.g., Hydroqual, 1998).

As detailed in Appendix A: Estimating Current and Future Dissolved Oxygen Distributions, the exact magnitude of dissolved oxygen improvements that can be expected for the estuary is uncertain. This stems from both scientific uncertainty as well as the unknown final management decisions from the possible range in future actions. For instance, both the magnitude of required NBOD load reductions and individual requirements for load reductions at facilities discharging to the estuary are unknown. Similarly, the reductions in ammonia and NBOD loading may have additional positive benefits on net primary production in the estuary that are difficult to anticipate or model. To acknowledge this uncertainty in future dissolved oxygen regimes, we have modeled and described two scenarios in Appendix A: a “Full Restoration” scenario where the anthropogenic dissolved oxygen sag is eliminated; and a “Moderate Restoration” scenario where a remnant dissolved oxygen sag of approximately 0.5 mg/L (~5% saturation) is still seen in the estuary, at least periodically.

Figures 11 portrays the restoration uplift and ecological effects when comparing current conditions to the Moderate Restoration scenario (see Appendix A for Full Restoration scenario details). Because dissolved oxygen varies during each day, among days and weeks, and across months and seasons in the estuary, the oxygen regime is best thought of as a “distribution” of oxygen concentrations that occur with different frequencies. Each of the three panels contrasts current conditions against Moderate Restoration predictions for one of the three key statistics modeled in this analysis.

Figure 11. Contemporary Dissolved Oxygen Sag vs Moderate Restoration Scenario for Three Modeled Statistics



Note. Current dissolved oxygen conditions (solid orange line) and Moderate Restoration scenario (solid blue line) presented for three statistics in dissolved oxygen distribution. “Typical” corresponds to median (50th percentile) summertime (June-July-August) daily average concentration; “Low” corresponds to 10th percentile of summertime daily average D.O. concentration; “Event” corresponds to 5th percentile of summertime daily ***minima*** D.O. concentrations (see Figure 4, Appendix A for additional details). Recommended 6.3 mg/L protective value (Academy of Natural Science of Drexel Univ, 2018) shown with horizontal dotted line.

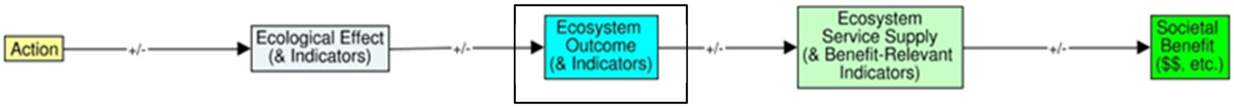
The bottom panel in Figure 11 presents “typical conditions” in the estuary for the period June-July-August, with median dissolved oxygen concentrations throughout the modeled areas in Zones 3, 4, and 5 of the estuary. The middle panel represents the periodic declines in dissolved oxygen (“low conditions”) observed every summer in the estuary, lasting from a few days to a week or more. Statistically, this second panel is a 10th percentile of the daily average dissolved oxygen concentrations, indicating that they occur (on average) about once every 10 days. The top panel represents the less frequent and more severe “event conditions” where instantaneous dissolved oxygen concentrations dip to their lowest levels every summer or every few summers. This third panel, statistically, is derived from daily minimum dissolved oxygen concentrations (the other two panels are from daily averages) and a lower, less frequent percentile (see Appendix A for specifics).

A comparison of the current and forecasted curves under the Moderate Restoration scenario demonstrates three key responses predicted as the ecological effects in this analysis. First, whereas “typical” oxygen conditions (orange line, bottom panel) decline steeply under the current regime, only a modest decline from upstream in Zone 2 down into Zone 3 is predicted in a Moderate Restoration scenario (blue line, bottom panel; approximately 0.5 mg/L or 5% oxygen saturation decline). This indicates that on a typical summer day, aquatic organisms in the Delaware Estuary would experience little or no difference in dissolved oxygen conditions across the estuary, providing adequate oxygen for all known sensitive species living in the estuary (i.e., D.O. remains above 6.3 mg/L; see Academy of Natural Sciences of Drexel University, 2018).

The second pattern to highlight under the Moderate Restoration scenario is the elimination of the regular to semi-regular periods where dissolved oxygen falls to between 3 and 4 mg/L (orange line, “event” conditions, top panel). Such concentrations are lethal for species such as Atlantic sturgeon, an endangered species, (e.g., Secor & Gunderson, 1998) and are far below the recommended protective thresholds for many of the Delaware Estuary’s sensitive species of fish and invertebrates such as striped bass, American shad, white perch, channel catfish, yellow perch, amphipods, and the eastern elliptio mussel (Academy of Natural Sciences of Drexel Univ, 2018). Although dissolved oxygen would continue to vary under the forecasted scenario above and below the “typical” or median conditions portrayed by the blue line in the lower panel of Figure 11, the oxygen distribution would no longer be predicted to fall below 4 mg/L into such acutely stressful conditions. Instead, the forecast dissolved oxygen concentrations (blue lines) under both “events” (upper panel) and “low” (middle panel) conditions remain at or above 5 mg/L even during these periodic depressions in dissolved oxygen. This is important biologically, with relevant dissolved oxygen criteria recommendations often having a “minimum” instantaneous threshold of 5 mg/L to protect aquatic life (e.g., U.S. EPA 1986; Pennsylvania Code, 2020).

Finally, Figure 11 shows that the forecast oxygen concentrations will increase by at least 1 mg/L for a significant portion of the Delaware Estuary under the Moderate Restoration scenario. For all three statistical benchmarks (event, low, typical), the uplift in dissolved oxygen exceeds 1 mg/L for 20 miles or more of the 133-mile-long Delaware Estuary, spanning nearly all of Zone 3 & 4. For the more severe “event” conditions, this predicted increase extends an even greater distance and covers most of Zones 3, 4, & 5 (see Appendix A for additional details). The prediction of a 1 mg/L or more improvement in dissolved oxygen extending across the Philadelphia-Camden-Chester reach of the Delaware River is thus robust to the statistical benchmark used for this important water quality threshold.

Ecosystem Outcome (& Indicators)



The blue boxes represent ecosystem outcomes, indicators, and impacts that we can measure of the action's ecological effects. Reductions in estuarine BOD loading will have measurable and direct effects on the magnitude and distribution of dissolved oxygen within the Delaware Estuary. BOD reductions will likewise have direct and indirect impacts on other water quality conditions and the biological assemblages living in and affected by both the changes to dissolved oxygen and the broader water quality regime.

For this analysis we estimate quantitatively how the Moderate Restoration scenario would improve juvenile survival rates for striped bass, American shad, and white perch. We also qualitatively assess how other ecological water quality indicators could improve with further improvements in dissolved oxygen conditions.

Increased Juvenile Survival Rates for Fish

Decades of research has documented the importance of dissolved oxygen for a host of fish species. This body of research finds, in particular, that early life stages (eggs, larvae, and juveniles) are significantly more sensitive to hypoxia than adults of the same species, including higher survival rates at increasing dissolved oxygen concentrations. With the urban corridor of the Delaware Estuary serving as important spawning and nursery grounds for many fish species, the increased survival rates for juvenile fish in these estuarine zones is therefore among the clearest and most easily quantified ecosystem outcomes resulting from the BOD load reductions and improvements to dissolved oxygen conditions.

The current analysis focuses on the response of three estuarine species that are both ecologically and economically important in the Delaware Estuary: American shad, striped bass, and white perch (see Appendix B: Estimating Increased Juvenile Survival for Striped Bass, American Shad, and White Perch). All three species are sensitive to reductions in dissolved oxygen, and all three species use the tidal waters of the Delaware Estuary within the historic zone of anoxia and hypoxia for their spawning and rearing each year.

The projected improvements to juvenile survival for all three species are summarized in Appendix B, Table B2 under the Moderate Restoration scenario and for the three key statistics in the dissolved oxygen distribution highlighted in this report. The greatest uplift in terms of increased survival is forecast when comparing current conditions to the forecast conditions under the "event" condition where dissolved oxygen falls to particularly low values for a period of days or weeks, but which is not necessarily observed every year. Such "events" can be particularly problematic for fish species and can contribute to wide variations in year class strength for these important game fish. Although periods of lower dissolved oxygen are an inherent part of the dissolved oxygen variability, future “events” are forecast to be much less severe and thus less problematic for juvenile fish and other aquatic species (see Figure 11). For the three species of fish included in the current analysis, the Moderate Restoration scenario is predicted to improve juvenile survival across the estuary between 25% and 47%. These increases demonstrate the severity of these dissolved oxygen periods when concentrations fall to between 3 mg/L and 4 mg/L, and the benefits to eliminating such extreme events.

For the more regular “Low” dissolved oxygen conditions experienced every year, juvenile survival under the Moderate Restoration scenario is expected to increase between 8% and 16% across the estuary for these three fish species. Finally, under the “typical” dissolved oxygen conditions, survival rates are forecast to increase by 3% to 5% across the estuary. The smaller changes in juvenile survival under median or “typical” summer conditions represent both the substantial improvements in D.O. that have been achieved over the last 50 years as well as the fact that ecological impacts often result from the variable swings in conditions and not from the typical conditions (Gaines & Denny, 1993).

It is important to note that the current analysis is somewhat conservative since it does not factor in expanding use of affected reaches of the river by these three species of fish. Shifts in spawning and rearing, particularly for American shad and striped bass, are expected to further increase the overall numbers and size class of these fish above the estimates in Appendix B.

It is also important to note that increases in survival are expected to be substantially greater for species of fish that are not commercially important at the moment, but which are even more sensitive to low dissolved oxygen. In particular, the federally endangered Atlantic sturgeon is understood to be the most sensitive species in the Delaware Estuary to low dissolved oxygen (Academy of Natural Sciences of Drexel University, 2018). The impacts from both low dissolved oxygen events and the improvement to juvenile survival may be substantially greater for Atlantic sturgeon than for any of the species included in this quantitative analysis.[15]

Other Ecosystem Indicators

The management actions evaluated in this analysis include the reduction of BOD loading to the estuary, primarily through reduced nitrogen-based BOD loads. The NBOD loading primarily results from the discharge of ammonia (NH3) from municipal wastewater treatment plants, which serves as a microbial energy source (thus its role in oxygen demand) as well as both a nutrient and a toxicant in the estuary. Alongside dissolved oxygen improvements, the suite of water quality changes anticipated in the future will lead to cascading effects on the entire estuarine ecosystem, from sediment microbes to plants and

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[15] Historically, the Delaware Estuary was the single most important spawning grounds for the Atlantic sturgeon, with an estimated 180,000 females in the Delaware River population alone (Secor & Waldman, 1999). Based on results from the caviar fishery from 1880 to 1900, it is estimated that 75% to 85% of the total harvest originated from the Delaware Estuary. The Atlantic sturgeon population collapsed, however, after this short period of intense and unsustainable harvest. Currently, the annual adult spawning run in the Delaware River is estimated to be less than 300 adult fish (Atlantic Sturgeon Status Review Team, 2007).

algae to invertebrates and freshwater mussels. Appendix C provides a summary of the conceptual model for how changes in BOD loading ripple through the ecosystem. Many of these pathways were difficult to quantify or predict in a way that could be incorporated into the economic analyses of this report. As a result, several important ecosystem improvements can only be described in a qualitative manner, resulting in an underestimate of the overall economic benefits from the BOD reductions and dissolved oxygen improvements.

A number of these ecosystem changes are valuable and important to highlight in terms of their qualitative benefits, even if their overall quantitative contribution could not be estimated at this time. First, a host of fish species from Atlantic sturgeon and shortnose sturgeon to bay anchovy and American eel will benefit both directly from increases in dissolved oxygen and indirectly from improvements in food and habitat. Similarly, many species of freshwater invertebrates (both benthic and planktonic) will benefit from the improved water quality, increasing both their abundance and their productivity in the estuary. Shifts in the relative concentrations of nutrients and the reduction in ammonia could lead to changes in algal composition and productivity, with a possible increase in relatively beneficial diatom algae in the food web. There will likely even be reductions in greenhouse gases as improved dissolved oxygen increases methane oxidation and reduces the anaerobic formation of nitrous oxides. The specific values for these various changes could not be accurately or completely modeled as part of the current project. Nevertheless, these broad improvements to ecosystem services are meaningful to both the natural ecology and the human ecology of this region.

Ecosystem Service Supply (& Benefit-Relevant Indicators)

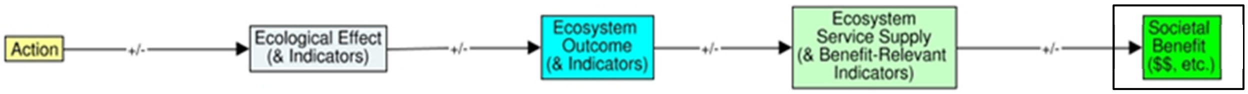
The light green box represents ecosystem services - services humans receive from nature - such as drinking water, clean air, recreational fishing days, raw materials, etc. We determined that key target ecosystem services supplied include recreation, aesthetics, food/nutrition, and other cultural & intrinsic value (Table 1). The quality (and value) of these services supplied are affected by the ecosystem outcomes and relevant indicators, and the societal benefits we receive from them can be measured in monetary terms.

Benefit-relevant indicators related to recreation commonly used to estimate value include days, trip-length, and positive experiences of birding, wildlife watching, hiking, fishing, and other water-related activities. Relevant food & nutrition supply indicators subject to changes in dissolved oxygen are commercial and recreational fishing populations and catch, alongside the health of the supporting aquatic habitats that maintain their viability. The indicators related to aesthetic value, which will experience positive impacts from dissolved oxygen improvements, cover riverfront views and general water quality improvements, including potentials in odor reduction, which can have spillover effects in how closely the community identifies with the river.

Table 1. Priority Ecosystem Services for Analysis

Target Ecosystem Service	Type of Ecosystem Service	Service Benefits Provided by the Estuary	Entities Affected by Dissolved Oxygen	What We Measure
`Recreation	Cultural	Bird and other wildlife watching, nature walks, recreational fishing, and boating	Businesses, visitors, and residents engaged in recreation in the estuary	Added value to: 1) Recreational anglers 2) Participants & nonparticipants in boating 3) Participants & nonparticipants in other waterside recreation activities
Food	Provisioning	Commercial fisheries & habitat to support viable fishing populations, other fish not for recreational or commercial catch, aquatic species e.g., plants, and fish for consumption	Commercial fisheries, local restaurants (other vendors, purchasers), consumers, subsistence anglers	1) Potential increase in commercial fishing value
Aesthetic Appreciation	Cultural	Riverfront views and experience associated with healthy waterways	Households within 2-miles of the Delaware River, those affected by appearance and smell of the river	1) Potential increase in home sale prices
Intrinsic	Cultural	Existence value, regional attraction due to a healthier, more thriving waterway	Businesses, residents, visitors, and other community members	(Not quantified) Increased community engagement and identity around the river, potential well-being, and mental health benefits

Societal Benefits



The endpoints of the diagram, in the bright green box, represent the estimated benefit in dollar terms that people in the Delaware Estuary would gain if dissolved oxygen is improved. Our modeled improvements in dissolved oxygen may have impacts on commercial and recreational fisheries and property values in the estuary. We can then estimate potential increases in commercial harvest, recreational fishing trips, boating, waterside recreation, and residential property value.

Although our modeling captures many of the key societal benefits, others were not quantifiable at this time (see Appendix C). These include landings of all D.O.-sensitive commercially-caught species within our study region (and those reared in our study region caught along the Atlantic coast), the food (provisioning) value of fish kept by recreational and subsistence anglers, commercial property values, non-single family/non-owner occupied residential property values, recreational activities in addition to boating and viewing, potential mental and physical health benefits and non-use values such as option and bequest. As a result, our analysis represents a conservative estimate of overall economic benefits. The final gross benefits, especially with elements such as commercial real estate included, would be significantly higher than our conservative values.

Fisheries

The Delaware Estuary provides critical spawning and nursery areas for many fish species and is both a spawning ground and a migratory route for American shad and striped bass, among others (Delaware River Basin Fish & Wildlife Management Cooperative, 2016). The most abundant[16] species found in recent seine surveys of the tidal Delaware River near-shore habitats were American shad, banded killifish, white perch, blueback herring, bay anchovy, and spottail shiners (New Jersey Department of Environmental Protection, 2018 & 2019). Other key species of the Delaware Estuary include weakfish, alewife, and Atlantic menhaden (Public Service Enterprise Group, 2004).

Our analyses of both commercial and recreational fisheries suggest important gains with improved dissolved oxygen conditions. The potential increase in ex-vessel values from improved D.O. levels for commercial American shad, striped bass, and white perch harvest in the Moderate Restoration scenario range as high as $728,000 annually, depending on the D.O. statistic used for the fishery uplift. Recreational benefits from increased water quality and improved dissolved oxygen levels corresponding to increases in anglers' catch per fishing trip could range from $3.3 million to $5.8 million for an expected increase of 0.5 fish or 1 fish per trip, respectively, for the study species.

The data, assumptions, and methodology used to arrive at these estimates are described below (and in Appendix D).

Commercial Harvest

Commercial landings of finfish and shellfish in Delaware and New Jersey (along the Atlantic coast and from the estuary) totaled 128.5 million pounds in 2016 with a revenue[17] of $203.1 million (National Marine Fisheries Service [NMFS], 2018). Shellfish such as blue crab and clams comprised the majority (87%) of this value (NMFS, 2018). Among the finfish found in the tidal portion of the Delaware River,

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[16] The data collected provides an annual abundance index for each species, reported as the number of individuals per seine haul, including young-of-year for index species such as striped bass and American shad (New Jersey Department of Environmental Protection, 2019).

[17] The NMFS (2018) defines landings revenue as the price that anglers are paid for their catch.

summer flounder, striped bass, and spot are considered key commercial species in the two states (NMFS, 2018).

In this study we focus on the ecologically and economically important striped bass, American shad, and white perch. Striped bass is only caught in Delaware's commercial fishery, as New Jersey commercial vessels are not allowed to land striped bass (Delaware River Basin Fish & Wildlife Management Cooperative, 2016). Although New Jersey is allocated a commercial harvest quota of striped bass under the Striped Bass Interstate Fisheries Management Plan (1981, as amended), this quota was transferred to the recreational fishing sector since the state does not allow netting or sale of striped bass (New Jersey Department of Environmental Protection, 2020).

Commercial harvest of American shad is allowed by both New Jersey and Delaware and occurs primarily south of the Delaware Memorial Bridge (Delaware River Basin Fish & Wildlife Management Cooperative, 2016). American shad is a target species for New Jersey commercial anglers, while landings of American shad reported by Delaware commercial vessels occur as bycatch from their striped bass fishery (Delaware River Basin Fish & Wildlife Management Cooperative, 2016).

White perch are economically important throughout the estuary, and one of the top five finfish species harvested commercially in the state of Delaware (Clark, 2017). Most commercial harvest occurs in the Delaware Bay, with landings also from the Delaware River and lower/tidal tributaries of the estuary (Clark, 2017; New Jersey Department of Environmental Protection, 2004).

Average annual commercial landings of striped bass, American shad, white perch, and all other species in the Delaware Estuary for the years 2000 through 2008 and 2009 to 2018 are presented in Table 2. These data were obtained, by subzone, from the Atlantic Coastal Cooperative Statistics Program (ACCSP; see Appendix D: Methods) and represent close to 100% of the true total for the three target species in this study (M. Rinaldi, ACCSP, personal communication, October 17, 2017). We focus on the years 2000 to 2018 because 2000 is regarded as the beginning of relatively stationary dissolved oxygen conditions in the estuary (Figure 3).

Table 2. Average Annual Commercial Landings in the Delaware Estuary, 2000-2008 and 2009-2018 (pounds[a])

Time Frame	Striped Bass	American Shad	White Perch	All Other Species
2000-2008	181,627	44,888	48,707	5,494,265
2009-2018	163,487	23,767	64,975	13,364,853

Note. Commercial landings data for the time frames were obtained from the Atlantic Coastal Cooperative Statistics Program (2019). For the 2000-2008 time frame, the three study species accounted for approximately 38% of total finfish catch in the estuary; for 2009-2018 they accounted for less than 4% of the total finfish catch. The finfish catch totals change significantly between the two timeframes.

[a] Live pounds: the calculated total poundage of product as a whole-weight for both finfish and shellfish (includes shell).

Combined landings of striped bass and American shad in the Delaware River have been declining since 1990, with the lowest levels observed between 2008 and 2015 (Delaware River Basin Fish & Wildlife Management Cooperative, 2016). The decline is most likely attributed to changes in the type of fishing gear allowed in Delaware's striped bass fishery and a declining number of New Jersey anglers seeking American shad since harvest reporting became mandatory in 2000 (Delaware River Basin Fish & Wildlife Management Cooperative, 2016).

In 2015, less than half (51) of the 111 commercial permits in Delaware were active, and of these, only 19 permit holders reported landings (Delaware River Basin Fish & Wildlife Management Cooperative, 2016). This decrease in Delaware commercial fishery participation is expected to continue; many anglers do not fish since they were allowed to transfer their striped bass quota to other licensed anglers.

In New Jersey, about three-fourths of the permits issued (47 of 61) allowing American shad harvest were active in 2016 (Delaware River Basin Fish & Wildlife Management Cooperative, 2016). Of these 47 permit holders, only nine reported landings. The number of commercial anglers in New Jersey is expected to continue to decline as the current anglers "age out of" the fishery and interest in the fishery continues to decline (Delaware River Basin Fish & Wildlife Management Cooperative, 2016).

However, improvements in water quality measures, such as dissolved oxygen, can contribute to healthier stocks of commercial fish populations and subsequently higher landings. We estimate the potential economic benefits to commercial fishing associated with improvements in dissolved oxygen levels by multiplying the most recent ex-vessel value[18] of each species by the predicted increase in juvenile survival under the Moderate Restoration scenario (as outlined in Appendix B).

Table 3. Potential Increase in Commercial Value for the Moderate Restoration Scenario across Three Statistical Benchmarks, Based on Average Annual Estuary Landings 2000-2008 and 2009-2018 (2018$)

Fish Species	2000-2008			2009-2018		
	Event	Low	Typical	Event	Low	Typical
Striped Bass	$664,989	$113,190	$42,446	$299,286	$50,942	$19,103
American Shad	$31,759	$12,703	$3,811	$8,408	$3,363	$1,009
White Perch	$31,501	$10,957	$3,424	$21,012	$7,308	$2,284
Total	$728,249	$136,850	$49,681	$328,705	$61,614	$22,396
Increase	31%	8%	3%	31%	8%	3%

Note. "Event" vs "Low" vs "Typical" statistical benchmarks correspond to those described in Appendices A & B for less common but more severe dissolved oxygen depression events, more regular "low" periods of dissolved D.O., and median summer conditions, respectively.

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[18] Ex-vessel value is defined as the price received at the point of landing for the catch (NMFS, 2018).

Results suggest that under the Moderate Restoration scenario, juvenile survival uplift could bring gains in commercial value for striped bass, American shad, and white perch in the Delaware Estuary ranging from about $22,000 to $728,000, depending on the dissolved oxygen condition and pounds harvested (Table 3). These gains represent increases of 3% to 31% compared to ex-vessel values without restoration. And, because the market price of these species can be 2 to 10 times the ex-vessel value, ultimate market benefits would be substantially greater (Kirkley, McConnell, & Ryan, 2000; ASMFC, 2010).

These are conservative estimates of the potential increase in striped bass and American shad values from improvements in the Delaware Estuary because fish from Delaware River stocks are also caught along the Atlantic coast. For example, a Massachusetts striped bass tagging study conducted from 1991 to 2014 found 19% of coastal striped bass originated from the Delaware River (Nelson, Boardman, & Caruso, 2015). The Atlantic States Marine Fishery Commission (2007) estimated that 11% of American shad off the coast of Virginia and Maryland and 13% off the New Jersey coast were Delaware River stock (since 1989). State-level commercial landings data from the NMFS include estuary landings, which prevents estimation of the value of coastal landings attributable to Delaware River stock.

We would also expect an increase in landings—and value—of other commercial species with juveniles sensitive to dissolved oxygen levels, including bluefish, summer flounder, and Atlantic menhaden (Academy of Natural Sciences of Drexel University, 2018). In the long-term, commercial values could also increase if species formerly important to the fishery—such as Atlantic sturgeon—recover enough to allow their harvest. However, even as increases in dissolved oxygen levels result in improved juvenile survival rates (Appendix B), it is possible there would be no subsequent increase in adult populations and thus in harvest and ex-vessel values (see Appendices B & D).

Recreational Fishing

The Delaware Estuary hosts many types of recreational (and subsistence) fishing, from shoreline fishing to fishing off charter and private boats. South of the Delaware Memorial Bridge, data from the National Oceanic and Atmospheric Administration's (NOAA) annual angler survey estimate that 1.45 million recreational angling trips were taken within the estuary in 2018 (NOAA, 2018). Striped bass or white perch were the primary or secondary target of anglers in 372,647 of those trips, or 26% of the total.[19]

North of the Delaware Memorial Bridge, data from the most recent Delaware River angler ("creel") survey estimates that 53,336 recreational fishing trips were taken within the estuary[20] in 2002[21] (Volstad et al., 2003). In this tidal section of the river, anglers targeted striped bass in 17,631 trips, or 33% of all trips (Volstad et al., 2003). Other species sought were river herring (alewife and blueback herring),

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[19] American shad was not named as a target species.

[20] Identified as the tidal portion of the Delaware River, to RM 133.

[21] No comprehensive creel survey of the Delaware River has been completed since 2002 (D. Pierce, Pennsylvania Fish & Boat Commission, personal communication, October 11, 2019). It should be noted that populations of key species such as striped bass have increased in the intervening 20 years and therefore contemporary numbers are expected to be higher.

channel catfish, largemouth bass, and smallmouth bass. The number of trips in which anglers targeted American shad or white perch was not provided but were likely included in the trips during which anglers sought other species (12% of the total) (Volstad et al., 2003).

In addition to the species named above, black drum, bluefish, channel catfish, spot, summer flounder, and weakfish are among the species sensitive to D.O. as juveniles (Academy of Natural Sciences of Drexel University, 2018). NOAA survey results estimate that black drum, bluefish, spot, summer flounder, and weakfish were sought in 541,532 trips south of the Delaware Memorial Bridge and channel catfish[22] were targeted in 14,671 trips north of the Bridge (Volstad et al., 2003).

Researchers have estimated the dollar value recreational anglers place on improvements in water quality (Parsons, Helms, & Bondelid, 2003; Massey, Newbold, & Gentner, 2006; Cropper & Isaac, 2011). Lipton and Hicks (1999) assessed water quality improvements, including as measured by dissolved oxygen levels, as a result of reduced nutrient loadings in the Chesapeake Bay (an estuary) and found that predicted improvements in water quality led to increases in anglers' expected catch rates and their perceived value of a fishing trip. Their results suggest an increase in the marginal expected catch rate of 0.5 fish per trip would correspond to an $8.39 increase in the value of a trip to anglers and an increased expected catch rate of one fish per trip would result in a $14.89 increase in the trip's value ($4.95 and $8.79 in 1994 dollars, adjusted to 2018 dollars). These results are comparable to an earlier study of striped bass anglers in the Chesapeake Bay. Norton, Smith, & Strand (1984) estimated the marginal value for an expected increase catch of one fish per trip at $16.15 ($9.53 in 1994$).

Excess nitrogen and phosphorus from sewage treatment plants and non-point sources such as agricultural and residential land use is a major focus of pollution control activities in the Chesapeake Bay watershed, along with dissolved oxygen targets (Lipton & Hicks, 1999). Because there are similar concerns in the Delaware Estuary, we use Lipton & Hicks' results to estimate the potential increase in recreational fishing benefits from improved dissolved oxygen levels and water quality. Benefits were calculated for a potential increase in expected catch rates of 0.5 and 1 fish per trip based on the number of trips in which anglers sought striped bass or white perch[23] (Table 4). We also estimate benefit gains for recreational anglers targeting other species sensitive to D.O. as juveniles (Academy of Natural Sciences of Drexel University, 2018).

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[22] No data for other sensitive species were provided.

[23] The number of trips for anglers seeking American shad or yellow perch was not available.

Table 4. Potential Increase in Recreational Fishing Benefits from Water Quality Improvements for Targeted Species (2018$)

Increase in Expected Catch Rate	Increase in Value per Trip	Striped Bass or White Perch[a] (millions)	Other Sensitive Species[b] (millions)	Total (millions)
0.5 Fish per Trip	$8.39	$3.3	$4.6	$7.9
1 Fish per Trip	$14.89	$5.8	$8.2	$14.0

[a] 390,278 trips

[b] Black drum bluefish, channel catfish, spot, summer flounder, and weakfish, 553,669 trips.

Other Recreational Activities

Researchers have found that participants in other outdoor recreation activities are willing to pay for improvements in water quality (Phaneuf, 2002; Lipton, 2003; Farber & Griner, 2000). To estimate the benefits of improved water quality to boaters and other river recreators, including improvements in dissolved oxygen levels, we multiply the total number of people age 16 and older in the study region by an estimate of the benefit of improved water quality (See Appendix D). Annual estimated benefits range from $3.5 million a year for shoreline activities to $4.0 million for boating.

Boating

Motorboating, canoeing, kayaking, jet skiing and paddle boarding are among the boating activities popular in the estuary (Delaware Riverkeeper Network, 2010; Delaware Riverkeeper Network et al., 2020). We multiply the number of people aged 16 and older (931,503) by a $4.25 annual average per person willingness to pay for improving river water quality for boating (Parsons, Helm, & Bondelid, 2003), resulting in an annual benefit of $4.0 million. The willingness-to-pay estimate for improved water quality applies to participants as well as nonparticipants.

Visiting the River

People visit the shore of the river for walking, biking, wildlife watching, picnics, and other activities. The same study region population is multiplied by an estimated $3.81 annual average per person willingness to pay for improving river water quality for waterside activities (Parsons, Helm, & Bondelid, 2003), resulting in annual benefits of $3.5 million. Again, the willingness-to-pay estimate applies to participants and nonparticipants.

Improved water quality can also contribute to increases in the number of days people participate in boating, fishing, and other water-based recreation activities. In turn, this can result in greater spending on trip-related purchases such as food, travel, kayak rentals, etc., which would likely generate higher revenue for local businesses and governments. The ecosystem service benefits estimated therefore represent only a portion of the potential increase in societal values.

Property Value

Waterways like the Delaware River provide important economic and ecological functions for users such as aesthetic benefits, recreational opportunities, industrial and household water supply, and habitat for native flora and fauna. It is no surprise then that properties along waterways are some of the most valuable and desirable properties (Krause, 2014). Having healthy and thriving waterways is a key driver of property value. A wide suite of existing literature demonstrates that improvements in water quality (measured through indicators like dissolved oxygen, chlorophyll, fecal coliform, water clarity, etc.) contribute to gains in property values (Florida Realtors, 2015; Guignet et al., 2019; Liu et al., 2017; Ara et al., 2006). In a global meta-analysis examining the connections between urban rivers and residential property values, researchers found that river views are associated with the greatest premium on housing prices (Chen et al., 2019). Anderson & West (2006) and Li & Brown (1980) determined that property values in urban areas increase with closer proximity to rivers.

While the clean-up of the Delaware River is heralded as a national success story, the expectations and aspirations for parts of the river still have not been elevated to the "fishable" and "swimmable" goals of the Clean Water Act (DRBC, 2019b). Because river restoration efforts positively impact residents' environmental perceptions toward urban rivers, engagement in restoration efforts may not only be beneficial toward public perceptions of waterways, but also provide monetary benefits in the form of property value gains (Chen et al., 2019). Understanding the extent of gains for homeowners can be useful information for decision makers trying to weigh costs of efforts, allowing them to more holistically assess where benefits associated with water quality improvements would accrue. We use the results from Netusil et al. (2014) (Table 5) to estimate property value gains in the Delaware Estuary as the study examines the relationship between dissolved oxygen, the spatial extent of property value benefits, and the shape of the benefit gradient across different markets.[24] The study found that a 1 mg/L improvement in dissolved oxygen levels in two urban watersheds in Oregon and Washington contributed to increases in sale-prices of single-family residential properties.

Table 5. Estimated Effects on Property Sale Prices of a 1 mg/L Increase in Dissolved Oxygen

Watershed	Zone of Influence			
	0 to ¼ mile	¼ mile to ½ mile	½ mile to 1 mile	1-mile to 2-mile
Burnt Bridge Creek (94.6% Urban Cover)	Not Significant	4.49%	2.95%	3.17%
Johnson Creek (66% Urban Cover)	13.71%	7.05%	8.18%	3.12%

Note. Adapted from “Valuing water quality in urban watersheds: A comparative analysis of Johnson Creek, Oregon, and Burnt Bridge Creek, Washington”, Netusil et al., 2014, *Water Resources Research*, 50(5), 4265.

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[24] No similar studies in estuarine settings were identified examining the spatially explicit real estate responses to dissolved oxygen changes.

Within the study region[25], there are 139,681 one-unit owner-occupied residential properties valued collectively at over $24 billion (See Appendix D). We determined the percentage of urban land cover by subzone and defined properties as either "urban" (following the results of the Burnt Bridge Creek watershed) or "less urban" (following the results of the Johnson Creek watershed). Furthermore, a different number of properties could experience gains in value depending on whether the subzone is predicted to experience a 1 mg/L improvement in dissolved oxygen under the various restoration scenarios. Our results are therefore grouped by restoration scenario, land cover, subzone, and zone of influence (See Appendix D).

Under the Moderate Restoration scenario (See Appendix D for the full results from both the Moderate and Full Restoration scenarios), we estimate a 1 mg/L improvement in dissolved oxygen levels or greater could contribute to property value gains of $540.9 to $835.4 million (Table 6).[26] The results estimate a one-time benefit of the total property value gains realized in the market if households within the specific zones of influence are sold at any point in the future. Based on the average number of years owners reside in their homes, we approximate that annually property value gains could range from $32.0 million to $48.4 million (U.S. Census Bureau, 2020c). (See Appendix D for data, calculations, and limitations to the analysis).

Table 6. Total Potential Property Value Gains Under the Moderate Restoration Scenario (2018$)

Conditions	Total Potential Property Value Gain (millions)
Event	$835.4
Low[a]	$540.9
Typical	$540.9

[a] Under the "Low" condition, the predicted D.O. change in subzone 4E falls slightly below the 1.0 mg/L threshold (0.8 mg/L) (see Appendix A). Because the predicted D.O. change exceeds this threshold both for "Event" and "Typical" conditions in this subzone, as for upstream subzones in the "Low" distribution, 4E is included in the predicted benefit from water quality improvements to maintain continuity in the forecasts.

It is important to note that the estimate of property value gains is conservative for three reasons (See Appendix D for more information). First, the gains are a partial estimate of total property value gains; additional real estate value increases from commercial or rental residential properties would substantially increase these estimates. Secondly, the estimates rely on the results from Netusil et. al (2014) in which sale price increases are tied to a 1 mg/L improvement in dissolved oxygen levels. Property value benefits tied to dissolved oxygen improvements are more likely to be continuous, with some benefits experienced below the 1 mg/L threshold and greater benefits associated with higher improvements in D.O. levels.

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[25] Between subzones 3A and 5C. See Appendix D for more details.

[26] We only estimate property value gains for owner-occupied single-family residential units within subzones predicted to have a 1mg/L or greater improvement in dissolved oxygen under the six restoration scenarios.

Third, Netusil et al. (2014) found no value gains in the Burnt Bridge Creek watershed within a quarter-mile of the waterbody. We hypothesize that gains in more urban settings within a quarter-mile of the river may be significant. In the nearby Chesapeake Bay, Walsh et. al (2017) found that improvements in water clarity, a frequently used indicator for water quality, contributes to increases in property value for waterfront properties. Other studies such as Bin & Czajkowski (2013) and Walsh et. al (2012) echo this trend; water quality improvements have statistically significant positive effects on waterfront homes. Acknowledging that property value benefits within the quarter-mile zone of more urban subzones are most likely non-zero, our overall valuation of property values could substantially increase.

This analysis relies heavily on the results of Netusil et al. (2014) because of its specificity in connecting the relationship between dissolved oxygen improvements in urban rivers, the spatial extent of property value benefits, and the shape of the benefit gradient across different markets in urban watershed settings. To our knowledge, there is no existing literature that provides the same level of specificity for analysis in tidal estuarine settings (Walsh et al., 2017). The results from Netusil et al. (2014) are not an outlier in the literature, however, as they reiterate the consensus that water quality improvements are associated with increases in property value. For further analysis, we recommend more sophisticated models be developed addressing the notion of continuous property value benefits within tidal estuarine settings, which would lead to a more refined overall valuation of benefits.

Property Value Benefits in Urban Cities

Cities like Philadelphia, Camden, Chester, and Wilmington are important examples of the nexus of urban impacts and environmental degradation. Being urban waterfront cities, the health of the Delaware River has a significant impact on residents' perceptions of how environmental impacts, direct or indirect, are addressed by decision makers. Elmqvist et al. (2015) found that restoring ecological functions in urban areas contributes to designing more livable, healthy, and resilient cities, and investing in ecological infrastructure is often economically advantageous.

Investing in technologies to improve dissolved oxygen could be a catalyst for economic uplift in vulnerable communities, and an important component of this analysis is understanding how and where benefits may accrue. Potential property value gains for one-unit owner occupied properties in the four target cities are presented in Table 7, and again, the results are grouped by restoration condition, land cover, subzone, and zone of influence (See Appendix D).

Under the Moderate Restoration scenario, properties within Philadelphia would see the most gains, collectively between \$313.5 to \$326.1 million, or an average of \$6,017-\$6,192 per household.[27] In Camden and Chester, there would be a collective gain of \$17.3 million and \$6.8 million under the Moderate Restoration scenario, or an average gain of \$2,293[27] and \$1,783 per household, respectively. Properties in Wilmington would see gains in the event condition of \$9.3 million, or an average of \$12,914 per household. Using the average number of years owners reside in their homes to approximate annual benefits, Philadelphia could see annual benefits ranging between \$19.6 and \$20.4

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[27] Averaged across all zones of influence for the event and low/typical condition, respectively. See Appendix D.

million. Properties in Camden and Chester could experience approximately $1 million and $300,000 in annual benefits, respectively, while Wilmington is conservatively estimated to see annual benefits in the event scenario of $500,000.

Results by zone of influence for the Moderate and Full Restoration scenarios can be found in Appendix D as well as data, calculations, and limitations to the analysis.

Table 7. Total Potential Property Value Gains Under the Moderate Restoration Scenario in the Cities of Philadelphia, Camden, Chester, and Wilmington (2018$)

City	Total Potential Property Value Gain (millions of 2018$)		
	Event	Low	Typical
Philadelphia	$326.1	$313.5	$313.5
Camden	$17.3	$17.3	$17.3
Chester	$6.8	$6.8[a]	$6.8
Wilmington	$9.3	$0	$0

[a] Under the “Low” condition, the predicted D.O. change falls slightly below the 1.0 mg/L threshold (0.8 mg/L) in subzone 4E, which encompasses the city limits of Chester (see Appendix A). Because the predicted D.O. change exceeds this threshold both for “Event” and “Typical” conditions here in Chester as well as for upstream subzones in the “Low” distribution, Chester is included in the predicted benefit from water quality improvements to maintain continuity in the forecasts.

It is worth mentioning again that the estimates presented in Table 7 are conservative for many of the same reasons. In addition, the variance of property value gains between the cities are due to differences in the number, and median property value, of owner-occupied residential properties, as well as which properties are set to gain property value from the 1 mg/L threshold (See Appendix D for details). Camden and Chester have substantially fewer one-unit owner occupied properties with a lower average value compared to properties in Philadelphia. Most one-unit owner-occupied properties in Camden are also renter-occupied, along with properties in Chester within one-mile of the river. In Wilmington, the city limits are almost exclusively bound by subzone 5B, which only crosses the 1 mg/L threshold in the Full and Moderate restoration “event” conditions. Because the supporting literature does not support the estimation of property value benefits on a continuous scale of dissolved oxygen improvements, the estimated gains are zero. Wilmington also has the fewest total number of owner-occupied properties compared to the other three cities. Although Wilmington has comparable median property values to Philadelphia overall, there are fewer total properties and the properties closest to the river consist of more renter-occupied units.

Using our method of analysis, the benefits in these four cities will undoubtedly be underestimated, but they must be understood in context. Hedonic price models as well as traditional cost-benefit analyses do not allow us to fully acknowledge how the property value benefits could contribute holistically to a dismantling of the environmental injustices in these historically economically underserved communities. Discriminatory siting of polluting facilities, unequal regulatory enforcement, and unequal political power are cited as contributors to systematic environmental injustices (Diaz, 2016). To address these issues, decision makers need to understand that prioritizing more equitable policies can lead to environmental justice, which will ensure that disadvantaged communities have equal access to both the tools and opportunities provided to more affluent communities.

How Water Quality Improvements Benefit Vulnerable Communities in the Estuary

The spatially explicit estimation of ecosystem service flows allows us to locate where dissolved oxygen improvements would occur, and who could benefit from the associated increases in ecosystem service values. While this analysis does not suggest a causal link (we do not estimate the statistical relationship between poverty or demographic characteristics and dissolved oxygen), it is important to consider that improvements in water quality can have positive environmental justice implications. Just as environmental degradation may be part of a vicious cycle involving social and economic degradation, similar forces could drive a virtuous cycle in which improvements in environmental quality engender economic opportunities and improvements in social conditions in vulnerable communities.

How vulnerable communities within the estuary might stand to benefit from D.O. improvements, or more general water quality improvements, requires understanding the ways in which the community and residents currently make use of their proximity to the Delaware River and how water quality improvements might affect that experience and use. To help answer that question, we conducted interviews with stakeholders from organizations in the cities of Chester, Camden, Philadelphia, and Wilmington focused on expanding river use to residents. (See Appendix E: Water Quality Improvement Interviews, for more information on who we interviewed, and the questions asked).

Each interviewee indicated that environmental injustices occur within their respective communities, citing issues such as disparities in the amount of funding available to address environmental harms, differences in post-industrial remediation efforts compared to nearby affluent communities, and a disproportionate concentration of environmentally intensive and obtrusive industries within vulnerable communities. When asked what the biggest environmental challenges are, the most frequently mentioned include combined sewer overflows (CSOs), general sewage issues (odor, aging systems, and clogs), air pollution, litter and debris polluting waterways and surrounding creeks, flooding, and a lack of remediation from residual industrial impacts. Because so many of the environmental issues relate to water quality, residents tend to have negative perceptions regarding the health of the estuary. In fact, respondents indicated that most residents in their communities would rate the health of the estuary as poor to below average because of a perception that the river is polluted from lingering industrial chemicals, litter along stream banks, and persisting odors from CSO’s and sewage plants.

Respondents noted that those in their communities generally possess an awareness of environmental and environmental justice issues but characterized a large gap between awareness and action due to the various economic challenges endured by residents which often take precedence in concern. Across the four cities, these economic challenges largely deal with issues related to systemic poverty which contribute to economic depression within the cities. More specifically, these issues include poor housing quality, underfunded education systems, lack of jobs, health concerns, public safety concerns, and a lack of political power and funding to address these issues.

Although respondents were nearly ubiquitous in their conclusion regarding the importance of addressing economic challenges first, they all acknowledged that improvements in water quality would be beneficial. Respondents noted that the number one barrier to increasing participation in activities along the river is limited access points to the Delaware River. Across the four cities, residents make use of the estuary for recreational opportunities such as fishing, boating, or rowing along the tributaries and in the main stem of the Delaware River, and riverfront activities such as nature walks along the shoreline, birdwatching, or picnicking. The level of engagement varies among residents, but if river and riverfront access were to expand (currently being hindered by industrial development), coupled with improvements in water quality, respondents see great potential for redevelopment along the waterfront. This could create economic and social benefits for vulnerable communities, including improved perceptions regarding edible fish[28], the psychological, physiological and quality of life benefits that come from time in nature, more access points for recreational boating and kayaking, riverfront parks and trails to connect communities, and fishing access.

Conclusions

Dissolved oxygen problems have plagued the tidal Delaware Estuary for over 100 years, resulting primarily from urban wastewater loadings of microbial food sources. Although the worst anoxic conditions have been eliminated and great strides have been made to restore aquatic life over the last 50 years, a D.O. sag persists from Philadelphia to the Delaware state line, with oxygen concentrations still falling below the antiquated criteria of 3.5 mg/L. Further improvements to D.O. are readily achievable using conventional technologies, and this additional treatment has been understood as a requisite step since the first pollution budget in the late 1960s. Increasing realization of both the opportunity for more complete restoration of dissolved oxygen, and the injustice toward human communities and the estuarine ecosystem embodied in the failure to act, have produced momentum to complete the restoration of D.O. for this estuary and attain the full potential of the ecosystem. In this report, improvements to dissolved oxygen ranging from less than 1 mg/L up to 2.5 mg/L are evaluated and modeled.

Actions that increase the estuary's dissolved oxygen and attenuate or eliminate the D.O. sag would improve juvenile survival rates for striped bass, American shad, white perch, and other species sensitive to dissolved oxygen concentrations, including endangered Atlantic sturgeon. This, in turn, would benefit regional commercial and recreational fisheries and those who participate in them. The quality (and value) of other ecosystem services supplied by the estuary would increase as well. These include benefits to other aquatic species, the food (provisional) value of fish caught and kept by recreational and subsistence anglers, property values, participation in recreational activities on and alongside the river, value to those who may not use the estuary, improved aesthetics, and reductions in greenhouse gases.

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[28] Edible fish vary by fish species and location. Some species are classified as "do not eat" while others have a recommended limit of intake per month.

Our modeling shows regional economic benefits for dissolved oxygen restoration would total at least $500 to $840 million for the portion of benefits estimated in the analysis.

Even with benefits exceeding half a billion dollars, our analyses represent a conservative estimate of all likely economic benefits. We have quantified the key societal values to the extent reliable data exist; others were not estimable at this time. Key needs include research in juvenile survival "uplift" for additional fish species sensitive to D.O. levels and surveys assessing how the regions' residents use and value the estuary. Estimates of additional financial, environmental, and social costs should be considered by policy makers when considering the tradeoffs between costs of D.O. improvements and the economic and environmental sustainability of the Delaware River watershed.

Restoring water quality could bring upon a cascade of positive effects for all communities within the estuary. Our spatially explicit estimation of ecosystem service flows allows us to locate where dissolved oxygen improvements would occur, and who could benefit from the associated increases in ecosystem service values. Improvements in water quality can have positive environmental justice implications as it may engender economic opportunities and improvements in social conditions in vulnerable communities. The quality of riverfront experiences may increase, as well as the demand for riverfront use. This could lead to more greenspace access for residents, particularly those economically disadvantaged, as well as improved access points to waterways.

Beyond the scientific value of the information developed, the results of our research and analyses can inform and guide the implementation of Delaware River restoration efforts, as well as allied efforts to leverage improved water quality into enhanced economic development opportunities in riverside and nearby communities.

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Appendix A: Estimating Current and Future Dissolved Oxygen Distributions

Multiple approaches can be used to estimate future dissolved oxygen conditions for the Delaware Estuary. In this analysis, we use empirical distributions of dissolved oxygen to forecast future conditions under reduced biochemical oxygen demand loadings from point source facilities. This approach differs from mechanistic water quality models (currently being developed by DRBC) and standard-setting approaches based on biological needs (e.g., U.S. EPA standards recommendations), with all three approaches having strengths and weaknesses (e.g., water quality models can be biased low and underestimate dissolved oxygen improvements; Sharp, 2010). No single approach will anticipate and predict both the human uncertainties and the ecological dynamics of a complex estuary, such as positive and negative feedbacks to changing water quality. As a result, no single approach will lead to completely accurate predictions of future conditions. A combination of approaches thus strengthens the rigor of evaluating possible future dissolved oxygen distributions in the estuary.

For the current research, multiple lines of evidence and multiple data sources were used to estimate both the current and future distributions of dissolved oxygen in each of the subzones of this project. In particular, three specific and biologically-relevant statistics serve as the focus for much of this report and were estimated for each subzone:

- "Event" Conditions – infrequent but biologically-stressful events; statistically defined in terms of the Daily Minimum dissolved oxygen as the 25th percentile of the daily 5th percentile conditions across the 92-day period of June-July-August using the relatively stationary data window of 2000-2018 (note: the other two statistics use the 24-hour Daily Average instead of the Daily Minimum).
- "Low" Conditions – depressed dissolved oxygen conditions expected more regularly and for longer durations than "Event" conditions; statistically defined in terms of the Daily Average (24-hour mean) dissolved oxygen as the 50th percentile (median) of the daily 10th percentile conditions across the 92-day period of June-July-August using the relatively stationary data window of 2000-2018.
- "Typical" Conditions – median of medians, and defined as the 50th percentile (median) of the daily 50th percentile (median) Daily Average (24-hour mean) dissolved oxygen concentration distribution across the 92-day period of June-July-August using the relatively stationary data window of 2000-2018.

The current data distributions (i.e., distribution across the 2000-2018 time window) were estimated using a combination of temporally-rich data at the USGS water quality sensors (RM 110.5 and 110.1 for stations #014670261 & 01467029; RM 100 for station #01467200; RM 83.5 for station #01477050; RM 54.1 for station #01482800) and the spatially-rich data from the DRBC-DNREC "Boat Run" surveys (DRBC 2018a; USGS-NWIS, 2020; PWD unpublished data). Full data distributions (i.e., cumulative distribution functions of both daily minima and 24-hour daily means) were estimable at each of the USGS sensor locations, while the spatial pattern of central tendencies were estimable from the Boat Run data. The "Event" and "Low" statistics were then spatially extrapolated based on the patterns of central tendencies and the full data distributions at the USGS sensor locations. Spatial patterns and central tendencies were also confirmed based on results from the Philadelphia Water Department modeling studies (PWD, 2016). The results from this analysis are presented in Table A1 for the three diagnostic statistics (and repeated in Table A2 to allow direct comparisons with predicted values).

Two future scenarios for dissolved oxygen distributions were then estimated for each subzone and each of the three key statistics in this analysis. First, a "Full Restoration" scenario was estimated where the anthropogenic dissolved oxygen sag in the urban corridor is entirely eliminated and dissolved oxygen fluctuates around a median saturation level of 85%. The 85% saturation level was selected as a reference equilibrium based on both within-estuary comparisons (USGS sensors at RM 110.5, 110.1, and 54.1) and external comparisons to regional and international characterizations of background oxygen saturation in estuaries (Best et al., 2007; Caraco et al., 2000; Clabby et al., 2008; Oslo-Paris Convention, 2013; Wasniak et al., 2007). The results from this Full Restoration analysis are presented in Table A1. A second Moderate Restoration scenario was then developed that did not forecast a complete amelioration of the dissolved oxygen sag in the estuary. For the Moderate Restoration scenario, a remnant dissolved oxygen sag of approximately 0.5 mg/L or 5% saturation (i.e., typical conditions fluctuate around 80% saturation rather than 85% saturation) was used to estimate statistical distributions of dissolved oxygen in each subzone of this analysis. The results from this analysis are presented in Table A2.

Table A1. Comparison Between Dissolved Oxygen Current Conditions and the Full Restoration Scenario for Three Key Statistical Benchmarks

Subzone	Current Distribution			Full Restoration Distribution		
	Event (mg/L)	Low (mg/L)	Typical (mg/L)	Event (mg/L)	Low (mg/L)	Typical (mg/L)
3A	4.70	5.30	6.30	5.80	6.20	6.95
3B	4.25	4.95	5.95	5.70	6.15	6.95
3C	3.75	4.55	5.55	5.60	6.05	6.90
3D	3.30	4.20	5.20	5.50	6.00	6.90
3E	3.30	4.20	5.20	5.50	6.00	6.90
3F	3.15	4.05	5.05	5.50	6.00	6.90
4A	3.00	3.90	4.90	5.50	6.00	6.90
4B	3.00	3.90	4.90	5.50	6.00	6.90
4C	3.15	4.05	5.05	5.50	6.00	6.90
4D	3.30	4.20	5.20	5.50	6.00	6.90
4E	3.90	4.70	5.50	5.50	6.00	6.90
5A	4.20	5.30	5.70	5.60	6.05	6.80
5B	4.30	5.50	5.80	5.65	6.10	6.70
5C	4.40	5.70	6.40	5.70	6.10	6.60

Table A2. Comparison Between Dissolved Oxygen Current Conditions and the Moderate Restoration Scenario for Three Key Statistical Benchmarks

Subzone	Current Distribution			Moderate Restoration Distribution		
	Event (mg/L)	Low (mg/L)	Typical (mg/L)	Event (mg/L)	Low (mg/L)	Typical (mg/L)
3A	4.70	5.30	6.30	5.65	6.10	6.85
3B	4.25	4.95	5.95	5.45	5.90	6.75
3C	3.75	4.55	5.55	5.20	5.70	6.60
3D	3.30	4.20	5.20	5.00	5.50	6.50
3E	3.30	4.20	5.20	5.00	5.50	6.50
3F	3.15	4.05	5.05	5.00	5.50	6.50
4A	3.00	3.90	4.90	5.00	5.50	6.50
4B	3.00	3.90	4.90	5.00	5.50	6.50
4C	3.15	4.05	5.05	5.00	5.50	6.50
4D	3.30	4.20	5.20	5.00	5.50	6.50
4E	3.90	4.70	5.50	5.00	5.50	6.50
5A	4.20	5.30	5.70	5.40	5.85	6.50
5B	4.30	5.50	5.80	5.55	6.00	6.50
5C	4.40	5.70	6.40	5.70	6.10	6.50

Appendix B: Estimating Increased Juvenile Survival for Striped Bass, American Shad, and White Perch

Increased D.O. concentrations will improve the growth, reproduction, and survival of many species in the Delaware Estuary, from small invertebrates to various bivalves and mussels to larger resident and migratory fish. A recent literature review for species inhabiting the Delaware Estuary summarizes both the lethal and sub-lethal effects documented in either lab studies or field studies, with an emphasis on oxygen-sensitive fish species (Academy of Natural Sciences of Drexel University, 2018). Yet as that study documents, individual studies for either lethal or sub-lethal responses across a wide range of dissolved oxygen conditions are sparse for any given species, precluding species-specific analyses for improved growth, reproduction, and survival under a range of forecasted dissolved oxygen scenarios.

Instead of species-specific estimation, the current research utilized a synthesis of survival curves for oxygen-sensitive species conducted by the U.S. EPA (1986). In that analysis, oxygen-sensitive freshwater fish species demonstrated similar dose-response relationships in terms of increased survival for juvenile life stages with increasing dissolved oxygen concentrations. The U.S. EPA synthesis served as the basis for a logistic regression statistical model of increasing juvenile survival probability with increasing oxygen concentrations from less than 2 mg/L to greater than 8 mg/L.

Three oxygen-sensitive fish species in the Delaware Estuary (striped bass, American shad, white perch) are important for both commercial and recreational fisheries, providing a means to estimate increased economic value for improvements in these species' populations. Predicting adult population size based on improvements in spawning and reproduction is challenging because of the various density-dependent and density-independent sources of mortality as fish age, including both natural mortality and fishing mortality, as well as other complexities inherent in population modeling. In the current analysis, only improvements in juvenile survival are predicted based on changes in dissolved oxygen distributions. These predicted increases in juvenile survival serve as an upper bound for possible increases in adult population size, acknowledging that actual adult population increases could be smaller.

Logistic regression curves derived from the U.S. EPA synthesis of oxygen-sensitive species were used in conjunction with the estimates for current and future dissolved oxygen data distributions to predict the percent survival of striped bass, American shad, and white perch eggs, larvae, and juveniles inhabiting each of the subzones of the current analysis. From the subzone estimates of increased survival, estuary-wide increases in survival for the three fish species were then estimated by combining the survival probabilities for each subzone of the estuary with estimates of the spawning and rearing distribution of these three species. During the 2000-2018 data window, detailed analyses of eggs, yolk-sac larvae, and post yolk-sac larvae distributions were completed under contract with the Salem Nuclear Generating Station during the 2002, 2003, and 2004 survey years (Public Service Enterprise Group [PSEG], 2002; PSEG, 2003; PSEG, 2004). Ichthyoplankton surveys during these years provided direct estimates of the timing and spatial distribution of reproductive efforts for the three target species (and others not analyzed here). These 2002-2004 data for eggs and larvae were used in a conservative estimate of the increased survival for striped bass, American shad, and white perch without expanding their spawning distribution into subzones where below-expected utilization has been noted (DRBC, 2015).

The results from the current analysis indicate moderate to large increases in juvenile survival for oxygen-sensitive species such as American shad, striped bass, and white perch in the Delaware Estuary with reduction or elimination of the dissolved oxygen sag. Integrated across all subzones, Table B1 provides the estimated increases under the Moderate Restoration scenario that are used for subsequent economic analyses. These predicted increases range as high as 47%. In particular, for the annual "Low" and for the "Event" conditions that likely serve as extreme events for young fish and may serve as population bottle-necks, future D.O. increases lead to between 8% and 47% increases in estuary-wide early live stage survival for oxygen-sensitive fish such as American shad, striped bass, and white perch. These increases are predicted even under the Moderate Restoration scenario where the D.O. sag is largely ameliorated but not completely eliminated.

Table B1. Predicted Estuary-Wide Increases in Percent Survival for Three Oxygen-Sensitive Fish Species with Moderate Restoration Scenario Improvements to Dissolved Oxygen Conditions

D.O. Condition	American Shad	Striped Bass	White Perch
Typical	3%	3%	5%
Low	10%	8%	16%
Event	25%	47%	46%

Note. Appendix A provides statistical definitions of "Typical", "Low", and "Event" dissolved oxygen conditions.

These predicted increases estuary-wide arise from sharp disparities in predicted juvenile survival within the D.O. sag subzones. With D.O. during periodic "Events" currently falling below 3.5 mg/L, juvenile survival in the heart of the oxygen sag (subzones 3D, 3E, 3F, 4A, 4B, 4C, 4D) is predicted to fall to as low as 16% to 26% during these events. Even under the more regular "Low" conditions seen annually, juvenile survival in the oxygen sag subzones is predicted to range from only 51% to 63% for oxygen-sensitive species. Under the Moderate Restoration scenario, future "Event" conditions are predicted to maintain juvenile survival above 80% since D.O. would remain at or above 5.0 mg/L. Likewise under the Moderate Restoration scenario, juvenile survival under the "Low" conditions of the future is predicted to always remain above 90%. Even under the median or "Typical" conditions, juvenile survival is predicted to rise an additional 10% to 16% in the subzones of the oxygen sag for oxygen sensitive species. Based on the available data, dissolved oxygen regimes in the Delaware Estuary remain in a critical transition zone where improvements are biologically meaningful.

It is important to note that two endangered fish species (Atlantic sturgeon and shortnose sturgeon) are among the most sensitive species in the estuary to dissolved oxygen (e.g., Campbell and Goodman, 2004; Niklitschek and Secor, 2009; Secor and Gunderson, 1998). Even the substantial increases in juvenile survival predicted for striped bass, American shad, and white perch (as high as 47%) likely underestimate the potential uplift for the two federally-endangered sturgeons utilizing the Delaware Estuary as critical habitat.

Appendix C: Conceptual Model of Ecosystem Response to Changes in BOD Loading

Because oxygen serves as one of the most basic requirements for all aerobic life, the absence or depression of dissolved oxygen concentrations in a setting like the Delaware Estuary will have far-reaching and dramatic consequences for the abundance and distribution of species in the estuary as well as for the biogeochemical functioning of the estuary as an ecosystem. The current economic analyses focus on a limited subset of these broad changes where quantitative predictions for their ecological response could be estimated and where the ecological changes could be valued in economic terms. This appendix provides a brief, qualitative description of the broader ecosystem responses that will result from the management actions to reduce BOD loadings from point source facilities. We note that the temperature-dependence of oxygen saturation in water (i.e., warmer water holds less oxygen), along with sea level rise and salinity intrusion (freshwater holds more oxygen than saltwater), translate to important implications from climate change on future dissolved oxygen dynamics. In this report, however, we have not attempted to look at the additive and interactive effects of climate change on future dissolved oxygen conditions.

A conceptual model outlining the ecosystem responses is shown in Figure C1. This conceptual model was developed iteratively through literature reviews and feedback from estuarine ecologists on earlier drafts of the conceptual model, but still represents a simplified portrayal of the estuary's complexity.[29] The ecosystem responses in the estuary stem from the current expectation for future management actions. Specifically, the most recent modeling of the estuary for dissolved oxygen emphasized the primary role of NBOD loading from point source facilities in creating the contemporary depression of dissolved oxygen in the urban corridor of the estuary (Hydroqual, 1998). The primary approach to ameliorate the oxygen sag is therefore expected to be the regulation and control of NBOD loading to the estuary from these point source facilities, with some additional CBOD reductions also possible.

Because the NBOD load derives largely from high ammonia concentrations in point source effluents, there are actually two first-order responses from the anticipated management actions. First, the primary effect of BOD controls is to increase summertime dissolved oxygen concentrations and reduce or eliminate the D.O. sag around Philadelphia, Camden, and Chester. The second effect will be the reduction in ammonia concentrations and loadings to this urban corridor, and the indirect effects of ammonia reductions beyond dissolved oxygen pathways.

The reduced BOD loading and increase in summertime dissolved oxygen provide direct and substantial benefits to various species of aerobic animals and microbial life in the estuary. With extensive research on the dissolved oxygen requirements of various fish species, particularly for early life stages, the

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[29] Particular thanks are extended to Dr. Pat Glibert (University of Maryland, Horn Point Lab); Dr. Denise Breitburg (Smithsonian Environmental Research Center); Dr. Stuart Findlay (Cary Institute of Ecosystem Studies); Mike Kaufmann (Pennsylvania Fish & Boat Commission); and Jim Falk (University of Delaware Sea Grant College Program, retired).

current research has been able to quantitatively estimate the increase in juvenile survival for three sensitive and economically important species in the estuary (striped bass, American shad, and white perch). This increase in juvenile survival for these and additional oxygen-sensitive species of fish in the estuary (shown in yellow in Figure C1) will lead to both increased populations of these fish species as well as increased food resources for fish and other predators in the food web. With Atlantic sturgeon documented to be the single most sensitive species of fish in the estuary, improvements to dissolved oxygen may be vital to recovering this endangered species and preventing the extinction of the genetically unique Delaware River population of Atlantic sturgeon.

Improvements to summertime dissolved oxygen will similarly benefit a broad range of invertebrate species in the estuary (shown in blue in Figure C1). From state-listed freshwater mussel species, to aquatic insects, to planktonic invertebrates, improvements to dissolved oxygen can increase survival and performance of these invertebrates within the food web. Like with juvenile fish species, these invertebrates serve as important links to higher trophic levels, with increases cascading upward to other invertebrates and predatory fish species in the ecosystem.

Dissolved oxygen increases during summer can also lead to reductions in greenhouse gas emissions from the estuary. Both through increased oxidation of methane and through reduced production of nitrous oxide in anaerobic sediments, the net flux of two powerful greenhouse gases out of the estuary is expected to be reduced through higher dissolved oxygen concentrations.

Beyond the direct dissolved oxygen pathways, both the indirect cascading effects and the reductions in ammonia can lead to additional important changes in the estuary’s ecosystem. First, ammonia inhibition of primary production has been demonstrated in similar estuarine settings, and inhibition of primary production has long been postulated for the freshwater tidal Delaware River (e.g., Yoshiyama and Sharp, 2006). The reduction in ammonia may therefore release algal populations, particularly diatoms, and lead to increased abundance and gross primary production in the estuary. Such increases in primary production could then lead to further improvements in dissolved oxygen (current algal blooms in the freshwater tidal river appear to have a net beneficial effect on oxygen concentration and saturation) and can provide additional food resources for higher trophic levels, magnifying the increases in secondary production and population sizes.

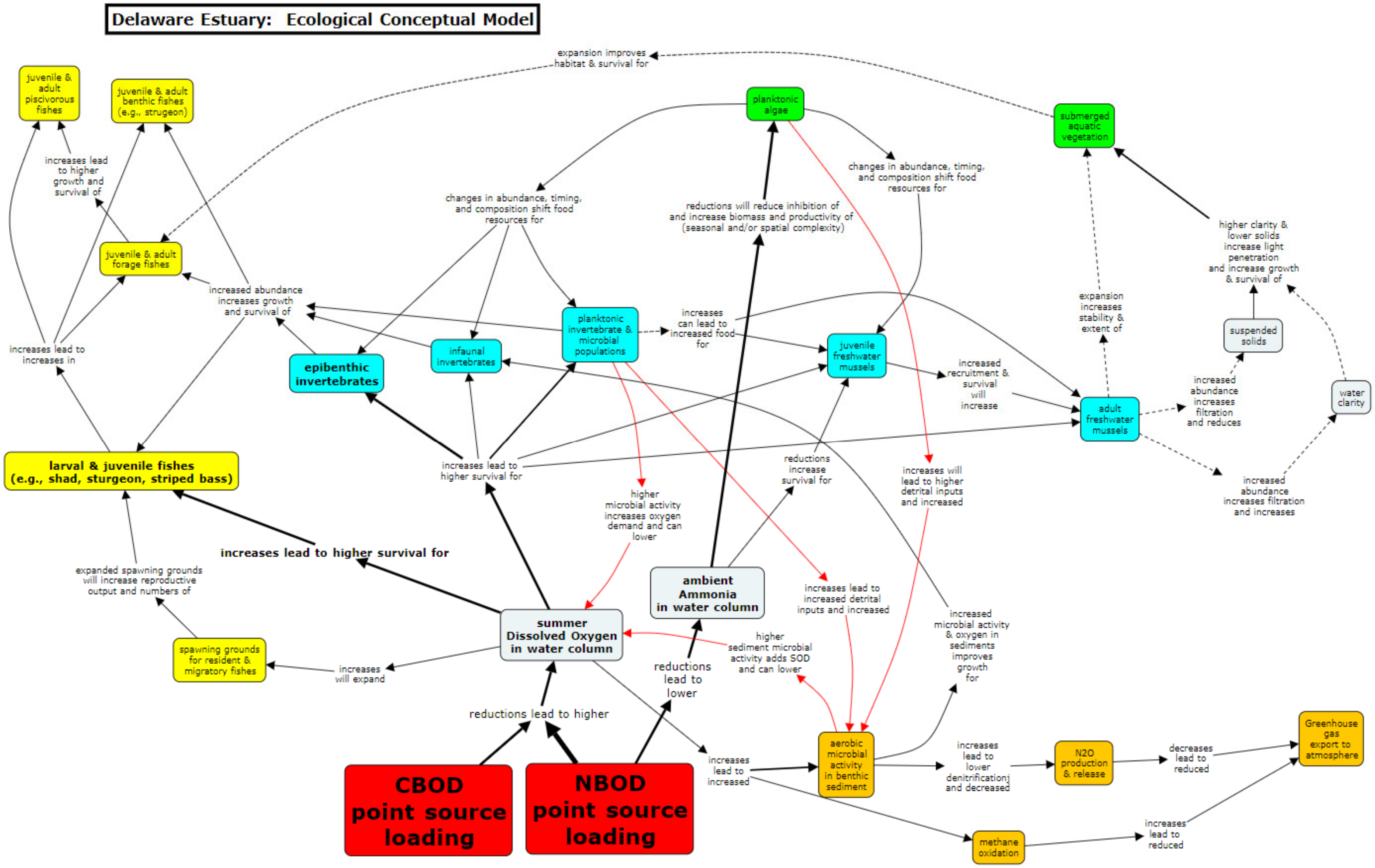
Because high ammonia concentrations can be toxic to many species, with freshwater mussels showing particular sensitivity to ammonia, the reductions in ammonia concentrations and loadings from point source facilities will increase the survival and fitness for many species in the estuary. Particularly because the estuary harbors strong and regionally important populations of two imperiled freshwater mussels (*Leptodea ochracea* and *Ligumia nasuta*), any reductions in ammonia toxicity could be important both for population sizes and for reducing the risk of extinction for these state-listed species.

Additional water quality benefits can be anticipated as indirect effects of changes in the ecosystem. For example, increases in freshwater mussel populations can both reduce total suspended solids in the water column and increase water clarity, leading to further improvements in primary production in the Delaware Estuary. Some association between freshwater mussels and important submerged plants (e.g., *Vallisneria americana*) has also been documented in the Delaware Estuary, opening a pathway for submerged plants to benefit from the reductions in BOD loading and ammonia concentrations. With aquatic plant beds serving a critical role for invertebrates and juvenile fishes, any expansion in aquatic plant beds could then further expand the populations and productivity of these higher trophic levels.

As shown with the red arrows in Figure C1, the increases in microbial and animal life in the estuary may also lead to negative feedback loops, particularly with increased respiration creating additional demand for dissolved oxygen in the estuary. These cascading effects in the food web are difficult to quantify, and such indirect effects play an important role in limiting the precision with which future dissolved oxygen conditions can be predicted using empirical methods (such as developed in this study) or mechanistic water quality models.

The conceptual model of the Delaware Estuary below begins to demonstrate the far-reaching effects of increasing dissolved oxygen for this ecosystem. But this model is a simple representation of the much more complex interactions among hundreds of species. As documented with the recovery from anoxic conditions 50 years ago, restoration of dissolved oxygen can have effects far exceeding original predictions (DRBC, 2015; Sharp, 2010). The full extent of the Delaware Estuary's response cannot be quantified at this time, and the current study models only a portion of the ecological changes that are quantifiable and valued in economic terms. Nevertheless, the anticipated changes are numerous and far-reaching, both ecologically and economically.

Figure C1. Simplified Conceptual Model of the Delaware Estuary Ecosystem Response to Reduced NBOD and CBOD Loading.



Appendix D: Methods

Commercial Fishing

Data

Commercial Harvest

Commercial landings[30] of striped bass, American shad, white perch, and all other species (finfish and shellfish) were obtained from the Atlantic Coastal Cooperative Statistics Program (ACCSP) by sub-area (Table D1) and allocated to the study subzones using ArcGIS. Due to data confidentiality constraints, ACCSP provided annual average landings for two time periods, 2000 to 2008 and 2009 to 2018, rather than annual values (Tables D2 and D3). Average landings for the three study species from 2000 to 2008 were 548,443 pounds a year, and 2,434,026 pounds annually between 2009 and 2018. The data provided by ACCSP represent close to 100% of the true total for our target species (M. Rinaldi, ACCSP, personal communication, October 17, 2017).

Table D1. Delaware Estuary ACCSP Sub-Area Codes and Corresponding Study Subzones

ACCSP Sub-Area Code	Sub-Area Name	Study Subzone
171	Delaware Bay - New Jersey	6
172	Delaware River - Delaware	4E
173	Delaware River Tributaries	4E[a]
185	Cape May Point to Fortescue	6
186	Fortescue to Hope Creek	6
187	Hope Creek to Commodore Barry Bridge	5A, 5B, & 5C
188	Above Commodore Barry Bridge	[b]
190	Broadkill River	6
194	Mispillion River	6
195	Murderkill River	6
197	St. Jones River	6
199	Delaware River - Delaware	5A, 5B & 5C
200	Delaware Bay - Delaware	6

Note. Sub-area codes were obtained from the Atlantic Coastal Cooperative Statistics Program (2019).

[a] The boundary for this sub-area is not available; it is located above sub-area 172 (subzone 4E, mainstem) (Matthew Heyl, New Jersey Fish and Wildlife, personal communication, October 3, 2019) and is approximated here as subzone 4E.

[b] The boundary for this sub-area is not available; it is located above sub-area 187 in the river mainstem (Matthew Heyl, New Jersey Fish and Wildlife, personal communication, October 3, 2019).

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[30] The NMFS (2018) defines landings as the poundage or number of fish unloaded by commercial fishers or brought to shore.

Table D2. Commercial Landings in the Delaware Estuary by Subzone, Average Annual 2000-2008 (pounds[a])

Subzone	Striped Bass	American Shad	White Perch	All Other Species[b]
5A, 5B & 5C	25,242	2,076	1,343	1,011,082
6	338,011	87,701	96,070	9,977,449
Total	363,253	87,777	97,413	10,988,531

Note. Commercial landings were obtained from the Atlantic Coastal Cooperative Statistics Program (2019).

[a] Average live pounds, the calculated total poundage of product as a whole-weight for both finfish and shellfish (includes shell)

[b] Finfish and shellfish

Table D3. Commercial Landings in the Delaware Estuary by Subzone, Average Annual 2009-2018 (pounds[a])

Subzone	Striped Bass	American Shad	White Perch	All Other Species[b]
4E[c]	-	-	-	151,379
4E	-	-	-	474,698
5A, 5B & 5C	74,014	3,760	7,883	50,991
6	1,547,538	186,813	614,017	132,499,565
Total	1.621,552	190,573	621,901	133,176,634

Note. Commercial landings were obtained from the Atlantic Coastal Cooperative Statistics Program (2019).

[a] Average live pounds, the calculated total poundage of product as a whole-weight for both finfish and shellfish (includes shell).

[b] Finfish and shellfish.

[c] This portion of subzone 4E (sub-area 173) is tributaries (ACCSP, 2019); although the boundary is unavailable, it is above mainstem sub-area 172 (Matthew Heyl, New Jersey Fish and Wildlife, personal communication, October 3, 2019) which is largely within subzone 4E.

Commercial Value

Ex-vessel prices, the prices received at the point of landing for the catch, of striped bass, American shad, and white perch, were obtained from the ACCSP for the Delaware Bay and a portion of the Atlantic Ocean off the coast of New Jersey and Delaware, NOAA Statistical Area 621 (Figure D1), in 2018$:

- Striped bass - $3.90/pound;
- American shad - $1.42/pound; and
- White perch - $0.70/pound.

Because the market price of fish can be 2 to 10 times the ex-vessel value (Kirkley, McConnell, & Ryan, 2000; ASMFC, 2010), ultimate market benefits would be substantially greater. For example, in 2014 the retail price of striped bass in Cape Cod was $17 to $26 per pound, while ex-vessel prices were $4 to $5 per pound (Fraser, 2014).

Figure D1. NOAA Fishing Area Codes

Calculations

Commercial value gains from improvements in D.O. levels in the Moderate Restoration scenario (Tables D4 and D5) were calculated by multiplying the 2018 average ex-vessel value of each species by the predicted increase in juvenile survival (Appendix B).

Table D4. Potential Increase in Commercial Value for the Moderate Restoration Scenario by Study Species, 2000-2008 (2018$)

Species	Ex-vessel Value	Increase in Juvenile Survival	Increase in Ex-vessel Value
Striped Bass	$1,414,870		
Event		47%	$664,989
Low		8%	$113,190
Typical		3%	$42,446
American Shad	$127,034		
Event		25%	$31,759
Low		10%	$12,703
Typical		3%	$3,811
White Perch	$68,481		
Event		46%	$31,501
Low		16%	$10,957
Typical		5%	$3,424
Total	$1,610,386		
Event		-	$728,249
Low		-	$136,850
Typical		-	$49,681

Note. The ex-vessel value is constant across conditions.

Table D5. Potential Increase in Commercial Value for the Moderate Restoration Scenario by Study Species, 2009-2018 (2018$)

Species	Ex-vessel Value	Increase in Juvenile Survival	Increase in Ex-vessel Value
Striped Bass	$636,778		
Event		47%	$299,286
Low		8%	$50,942
Typical		3%	$19,103
American Shad	$33,630		
Event		25%	$8,408
Low		10%	$3,363
Typical		3%	$1,009
White Perch	$45,677		
Event		46%	$21,012
Low		16%	$7,308
Typical		5%	$2,284
Total	$728,593		
Event		-	$328,705
Low		-	$61,614
Typical		-	$22,396

Note. The ex-vessel value is constant across conditions.

Urban Cities

There are commercial fishing ports located in Wilmington and Chester, subzones 5B and 4E, which reported landings of American shad, striped bass, and white perch 2000-2018 (ACCSP, 2019; Tables D2 and D3). These ports, located in economically disadvantaged communities, would particularly benefit from increases in commercial harvest resulting from improvements in dissolved oxygen levels.

Limitations

The increase in the estimated commercial values of striped bass and American shad[31] based on increased juvenile survival rates may represent an underestimate of benefits attributable to a rise in D.O. because fish from Delaware River stocks are caught along the Atlantic coast as well as the Delaware Estuary. For example, a striped bass fish tagging study conducted from 1991 to 2014 found that 19% of coastal striped bass originated from the Delaware River (Nelson, Boardman, & Caruso, 2015). Similarly, the Atlantic States Marine Fishery Commission (2007) estimated that 11% of American shad along the coast of Virginia and Maryland, and 13% along the New Jersey coast, were Delaware River stock, based on DNA and tag-recapture programs. State-level commercial landings data from the NMFS are for estuary and coastal landings combined; we are not able to estimate coastal landings separately.

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[31] White perch are rarely found outside of the estuary (Clark, 2017).

The potential increases in values for our three study species represent a portion of the total increase in commercial fishing values that could be experienced with improvements in D.O. levels if these improvements benefit other commercial species. However, as we estimate how increases in dissolved oxygen levels result in improved juvenile survival rates (Appendix B), it is also possible there would be no increase in harvest as adult populations may not mirror the changes in juvenile survival.

Lastly, we use average 2018 ex-vessel prices to estimate the potential value of increased harvest; these prices vary from year-to-year depending on a number of factors. Between 2007 and 2016, for example, the ex-vessel price of striped bass in Delaware ranged from $2.07 to $4.41 per pound (2018$) (NMFS, 2018). The marginal dollar value of increased landings in the future would depend on then-current ex-vessel prices and the increase in harvest (pounds).

Recreational Fishing

Data

Recreational Fishing Trips

The number of fishing trips by recreational (including subsistence) anglers in the Delaware Estuary was obtained from the National Oceanic and Atmospheric Administration (NOAA) for the portion of the estuary south of the Delaware Memorial Bridge, and from the most recent Delaware River creel survey for the portion of the estuary north of the Delaware Memorial Bridge. Survey data from NOAA's Marine Recreational Information Program[32] indicates there were 1.45 million trips in the estuary in 2018 (NOAA, 2019). Striped bass or white perch were identified as the primary or secondary targets of anglers in 372,647 trips, 26% of the total. (American shad was not named as a target species.)

North of the Delaware Memorial Bridge, there were an estimated 53,336 recreational fishing trips in the estuary (identified as the tidal portion of the river, to RM 133) in 2002[33] (Volstad et al., 2003). These tidal trips represented over a third (37%) of all trips in the Delaware River between the Delaware Memorial Bridge and Downsville New York (Volstad et al., 2003). Anglers targeted striped bass in 17,631 trips, or 33% of all trips (Volstad, et al., 2003). Other species sought were river herring, channel catfish, largemouth bass, and smallmouth bass. The number of trips during which anglers targeted American shad or white perch was not provided but may be included in the trips during which anglers stated they sought "other species" (12% of total trips) (Volstad et al., 2003).

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[32] Obtained from Marine Recreational Information Program recreational fishing survey data for 2018, downloaded from the website (NOAA, 2019). The data extract was further limited to include only observations for the Delaware Estuary and target species. Each record represents one angler intercept and was expanded to total trip estimates using sample weight for each record.

[33] The study by Volstad et al. (2003), completed for the Pennsylvania Fish & Boat Commission, is the most recent creel survey available (D. Pierce, Pennsylvania Fish & Boat Commission, personal communication, October 11, 2019). See Tables 3-5a and 3-7.

We expect improvements in dissolved oxygen levels may also increase juvenile survival rates of other recreational fish species sensitive to dissolved oxygen, as identified by a recent study (Academy of Natural Sciences of Drexel University, 2018). Species sensitive to dissolved oxygen as juveniles and named as target species by recreational anglers include black drum, bluefish, spot, summer flounder, and weakfish. NOAA's recreational fishing survey estimates 539,028 trips in the estuary in 2018 (NOAA, 2019) during which these five species were targeted. North of the Delaware Bridge, channel catfish was sought in 14,671 trips; no other sensitive species studied by Academy of Natural Sciences of Drexel University were identified as targets (Volstad et al., 2003).

Angler Benefits

Several studies assess the effect of water quality changes on recreational fishing catch rates and angler benefits, but relatively few focus on changes in dissolved oxygen levels. Research on the effect of a 25% increase in D.O. on summer flounder fishing in Maryland's coastal bays found anglers value a 50% increase in the catch rate (about one fish) at $5.26[34] (2018$; $4.22 in 2006$) (Massey, Newbold, & Gentner, 2006). The value of an increase of one fish per trip for bottom fish in Maryland reported by Hicks et al. (1999) was $3.68 ($2.44 in 1999$).

We use the results of a study examining the role of improved water quality, including dissolved oxygen, in the Chesapeake Bay on expected catch rates of striped bass. Lipton & Hicks (1999) found an increase in the expected catch rate of 0.5 fish per trip could result in a $4.95 increase in the value of a trip to anglers and an increased expected catch rate of one fish per trip could result in an $8.79 increase in the value of a trip (1994$). In 2018 dollars, this corresponds to an increase of $8.39 and $14.89 per trip, respectively.[35]

Calculations

Study Species

The increase in recreational fishing benefits was calculated for a potential increase in expected catch rates of 0.5 and 1 fish per trip based on the number of trips during which our study species were named as targets by anglers—striped bass and white perch. Benefits from the expected increase in catch rates of 0.5 fish per trip and 1 fish per trip are estimated at $3,274,426 and $5,811,228, respectively.

Benefits are calculated using the following equation:

> Recreational Fishing Benefit, Study Species (2018$) = Number of Trips (by subzone) x Increase in Value Per Trip (2018$)

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[34] This is reported as the "value per choice occasion" which should be smaller than per trip estimates (all else equal) because there are more choice occasions than trips taken. (In the stated choice survey, the respondents were asked to choose between two alternative summer flounder trips and a "do something else" option.)

[35] These estimates do not account for the potential increase in the number of fishing trips as a result of an increase in expected catch.

Where:

- Number of Trips (by subzone) = 372,647 trips in subzone 6 or 17,631 trips in subzones 1-5
- Increase in Value Per Trip (2018$) = $8.39 per trip (increase in catch rate of 0.5 fish per trip) or $14.89 per trip (increase in catch rate of 1 fish per trip)

For an increase in expected catch rate of 0.5 fish per trip:

- 372,647 trips (subzone 6) x $8.39/trip = $3,126,506
- 17,631 trips (subzones 1-5) x $8.39/trip = $147,920
- **Total = $3,274,426**

For an increase in expected catch rate of 1 fish per trip:

- 372,647 trips (subzone 6) x $14.89/trip = $5,548,710
- 17,631 trips (subzones 1-5) x $14.89/trip = $262,518
- **Total = $5,811,228**

Other Sensitive Species

We also estimate the increase in recreational fishing benefits for a potential increase in expected catch rates based on the number of trips in which anglers sought other species sensitive to D.O. levels as juveniles.

Benefits are calculated using the following equation:

> Recreational Fishing Benefit, Other Sensitive Species (2018$) = Number of Trips (by subzone) x Increase in Value Per Trip (2018$)

Where:

- Number of Trips (by subzone) = 539,028 trips in subzone 6 (black drum, bluefish, spot, summer flounder, weakfish) and = 14,671 trips in subzones 1-5 (channel catfish)
- Increase in Value Per Trip (2018$) = $8.39 per trip (increase in catch rate of 0.5 fish per trip) or $14.89 per trip (increase in catch rate of 1 fish per trip)

For an increase in expected catch rate of 0.5 fish per trip:

- 539,028 (subzone 6) x $8.39/trip = $4,522,444
- 14,671 trips (subzones 1-5) x $8.39/trip = $123,090
- **Total = $4,645,535**

For an increase in expected catch rate of 1 fish per trip:

- 539,028 trips (subzone 6) x $14.89/trip = $8,026,126
- 14,671 trips (subzones 1-5) x $14.89/trip = $218,452
- (channel catfish)
- **Total = $8,244,578**

Limitations

The potential increase in benefits to recreational anglers south of the Delaware Memorial Bridge, subzone 6, is attributed to 2018 trip data from NOAA. We assume the number of trips, by target species, is indicative of future conditions. Angler benefits for subzones 1-5, north of the Bridge, rely on a 2002 creel survey, the most recent data, which we accept as the best approximation of future participation because there has been no survey since then (D. Pierce, Pennsylvania Fish and Boat Commission, personal communication, October 11, 2019). The degree to which adult fish populations may increase as a result of increased juvenile survival is uncertain, and we have assumed such increases will result in recreational anglers catching more fish.

Estimates for the economic benefit to anglers of catching more fish necessarily rely on a Chesapeake Bay study of striped bass, the only recent study we identified in a region near the Delaware Estuary. The results are driven by the spatial distribution of low dissolved oxygen and would require a model run specifically for the Delaware Bay for better value estimates (Lipton, personal communication, October 8, 2019). The impact of higher dissolved oxygen levels on catch rates varies with species, so ideally separate studies would be conducted for individual species (Cropper & Isaac, 2011).

Other Recreational Activities

Researchers have found that participants in other outdoor recreation activities are willing to pay for improvements in water quality. In the Chesapeake Bay, registered boaters (power and sail) were asked to rate water quality as poor, fair, good, very good, or excellent (Lipton, 2003). Survey results suggest the boaters were willing to pay an average of $92 per year for a one-step improvement in water quality (e.g., from fair to good), with a median willingness to pay of $25.52 per year (2018$) (Lipton, 2003; reported in 2000 dollars of $63 average and $17.50 median, respectively). A survey of recreational uses of lakes, rivers, and coastlines in six New England states found that the annual average per person willingness to pay for improving river water quality (from medium to high[36]) ranged from $3.15 for fishing, $3.81 for viewing,[37] and $4.25 for boating use (reported in 1994 dollars as $1.86 for fishing, $2.25 for viewing, and $2.51 for boating uses; adjusted to 2018 dollars) (Parsons, Helm, & Bondelid, 2003). These values are for participants as well as non-participants.

In North Carolina, a study of the benefits of ambient water quality improvements in river basins and watersheds used travel costs as the implicit price of a recreation visit. Results suggest a mean willingness to pay for improved water quality of 24 cents per day trip across all watersheds in the state, with a range from $0 to $2.04 per day trip in 2018 dollars (Phaneuf, 2002; reported as 17 cents per day trip across all watersheds in the state, with a range from $0 to $1.44 per day trip (assumed 2001 dollars).

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[36] Water quality is defined in terms of biological oxygen demand, total suspended solids, dissolved oxygen, and fecal coliform levels. Sites with medium water quality have some game fishing and usually few visible signs of pollution. Sites with high water quality are suitable for extensive human contact, have the highest natural aesthetic, and support high quality sport fisheries” (Parsons, Helms, & Bondelid, 2003).

[37] The survey defined viewing as trips where the primary purpose was to visit a beach or waterside for picnics, nature study, or other purposes.

Phaneuf (2002) notes these estimates should be interpreted as underestimates because the calculation does not consider an increase in the number of trips taken due to the quality improvement.

Data

Study Region Population

We obtained the number of people in our study region aged 16 and older from the U.S. Census Bureau (2020). Of the 1,170,210 people in the study area (within two miles of the Delaware Estuary), 931,503 are 16 years old or older (80%). This subgroup is identified because values in this section are estimated using data from the National Survey of Recreation and the Environment, which surveys individuals 16 years old and older (National Survey of Recreation and the Environment, 1999; Parsons, Helm, & Bondelid, 2003).

Calculations

To estimate the benefits of improved water quality, including dissolved oxygen levels, to boaters and those that visit the river for other activities, we multiply the study region population 16 years old and older by an estimate of the average per person willingness to pay for improving river water quality from medium to high (Parsons, Helm, & Bondelid, 2003).

Boating

Boating is a popular recreational activity in the estuary, including motorboating, canoeing, kayaking, jet skiing and paddleboarding (Delaware Riverkeeper Network, 2010; Delaware Riverkeeper Network et al. 2020). The identified population is multiplied by the $4.25 (2018$) annual average per person willingness to pay for improving river water quality for boating (Parsons, Helm, & Bondelid, 2003).

- 931,503 people age 16 and older * $4.25 per person = $4.0 million annually

Visiting the River

People visit the shores of the estuary for walking, biking, birdwatching and other activities. We multiply the identified population by $3.81 (2018$), the annual average per person willingness to pay for improving river water quality for viewing and other pursuits (Parsons, Helm, & Bondelid, 2003).

- 931,503 people aged 16 and older * $3.81 per person = $3.5 million annually

Improved water quality can contribute to increases in the number of days people participate in boating, fishing, and other water-based recreation activities. In turn, this can result in more trips and/or greater spending on trip-related purchases such as food, travel, kayak rentals, etc., which benefits local communities. For example, saltwater anglers in New Jersey spent an average of $970 per trip in 2011, and in Delaware anglers averaged $387 per trip (2018$; U.S. Fish and Wildlife Service, 2011). Food and lodging, transportation, and other trip costs represent about two-thirds of total expenditures with equipment comprising the balance.

Limitations

The benefits for boating and waterside recreation are estimated based on the number of people in our study region (a 2-mile zone adjacent to the river). Because we expect residents beyond our study area would visit the estuary and similarly benefit from water quality improvements, the values calculated above are likely underestimates.

Property Values

Data

Household Counts

For each census tract within two miles of the Delaware River boundary, we estimate the number of owner-occupied housing units using U.S. Census Bureau 2013-2017 American Community Survey 5-Year estimates. Estimating the number of single-family residential properties is necessary because we draw on the results from Netusil, Kincaid, & Chang (2014), which estimates sale price increases associated with dissolved oxygen improvements for single-family residential properties. (See next section, "Property Value".) Staff at the U.S. Census Bureau informed us that the total number of one-unit structures in a tract is representative of the number of single-family homes (U.S. Census Bureau, personal communication, September 2019; U.S. Census Bureau, 2018a). To determine the number of single-family homes that are owner-occupied (proxy for single-family residential properties), the percentage of owner-occupied units within a tract is multiplied by the total number of one-unit structures in a tract (U.S. Census Bureau, 2018b).

Many tracts fall within two subzones.[38] Since each subzone is associated with a different level of improvement in dissolved oxygen (See Appendix A), total household counts by subzone are calculated proportionately by area using ArcGIS software.[39]

Household counts within each zone of influence (a quarter-mile to half-mile, half-mile to one-mile, and one-mile to two-mile) were also obtained by subzone using the proportional area method.[40] This produces an estimate of the number of owner-occupied single-family residential properties by tract, zone of influence, and subzone. Table D6 shows the total household count by subzone within each zone of influence.

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[38] DRBC subzone boundaries were slightly adjusted to better align with census tract and other political boundaries.

[39] For example, if tract X has a total of 100 owner-occupied single-family housing units, and 40% of tract X's area is within subzone 3A and 60% of the subzone is within subzone 3B, we would estimate that 40% and 60% of the households are within subzones 3A and 3B, respectively.

[40] Using the hypothetical information from tract X in footnote 39, if 40% of households are within subzone 3A and 10% of tract X's area in subzone 3A falls within the half-mile to one-mile zone of influence, then four owner-occupied single-family residential properties would be counted as within the half-mile to one-mile zone of influence in subzone 3A for tract X.

Table D6. Total Number of Owner-Occupied Single-Family Properties by Subzone and Zone of Influence

Subzone	Land Classification	Number of Properties			
		0-¼ mile	¼-½ mile	½ -1 mile	1-2 mile
3A	Urban	848	1,925	6,293	13,591
3B	Urban	276	396	938	2,528
3C	Urban	1,079	3,073	7,330	13,536
3D	Urban	901	1,676	2,967	6,068
3E	Urban	164	1,275	5,555	11,630
3F	Urban	428	532	1,918	6,818
4A	Urban	190	233	314	1,116
4B	Less Urban	178	163	307	1,337
4C	Less Urban	265	217	376	1,416
4D	Less Urban	435	432	1,245	6,647
4E	Less Urban	381	481	1,729	5,177
5A	Less Urban	527	697	2,268	5,118
5B	Less Urban	181	242	646	2,135
5C	Less Urban	1,174	1,160	2,595	8,554

Note. Data for owner-occupied one-unit structures is from the U.S. Census Bureau (2018a and 2018b).

Property Value

The U.S. Census Bureau's 2013-2017 American Community Survey provides five-year average estimates of median housing value by tract for owner-occupied housing units (U.S. Census Bureau, 2018c). Total property value estimates are calculated by multiplying the median housing value by tract and the number of owner-occupied single-family residential properties. Table D7 shows the total existing property value by subzone within each zone of influence.

Table D7. Total Existing Property Value of Owner-Occupied Single-Family Properties by Subzone and Zone of Influence (2018$)

Subzone	Land Classification	Total Existing Property Value (millions)			
		0-¼ mile	¼-½ mile	½ -1 mile	1-2 mile
3A	Urban	$137.0	$234.5	$742.8	$1,909.8
3B	Urban	$39.5	$57.4	$125.8	$295.3
3C	Urban	$192.1	$564.3	$1,169.7	$1,532.2
3D	Urban	$359.0	$651.2	$830.6	$1,755.8
3E	Urban	$15.8	$269.1	$968.8	$2,090.2
3F	Urban	$49.5	$87.3	$380.5	$1,279.6
4A	Urban	$50.5	$65.5	$66.2	$191.1
4B	Less Urban	$29.9	$26.6	$50.8	$241.5
4C	Less Urban	$40.3	$33.3	$62.3	$252.8
4D	Less Urban	$64.8	$63.9	$197.0	$1,228.3
4E	Less Urban	$41.6	$44.7	$143.1	$723.6
5A	Less Urban	$114.0	$148.6	$495.1	$1,391.4
5B	Less Urban	$25.9	$35.9	$102.6	$281.0
5C	Less Urban	$240.8	$235.5	$516.9	$1,721.9

Note. Data for property value of owner-occupied one-unit structures is from the U.S. Census Bureau (2018c).

Length of Residence

The U.S. Census Bureau's 2013-2017 American Community Survey provides five-year average estimates of the median year a household moved into a unit by tenure at the tract level (U.S. Census Bureau, 2020c). Tables D8 and D9 show the average length of residence by subzone and city for owner-occupied homes. Length of residence data was used to approximate annual property value benefits, assuming that owner-occupied units will be sold based on the average length of residence. For example, annual property value benefits in subzone 3A is approximated by 1/16th of the total property value benefits in that subzone.

Table D8. Average Length of Residence for Owner-Occupied Units by Subzone

Subzone	Length of Residence (years)
3A	16
3B	17
3C	18
3D	14
3E	17
3F	18
4A	18
4B	19
4C	16
4D	18
4E	20
5A	17
5B	17
5C	18

Note. Data for average length of residence is from the U.S. Census Bureau (2020c).

Table D9. Average Length of Residence for Owner-Occupied Units by City

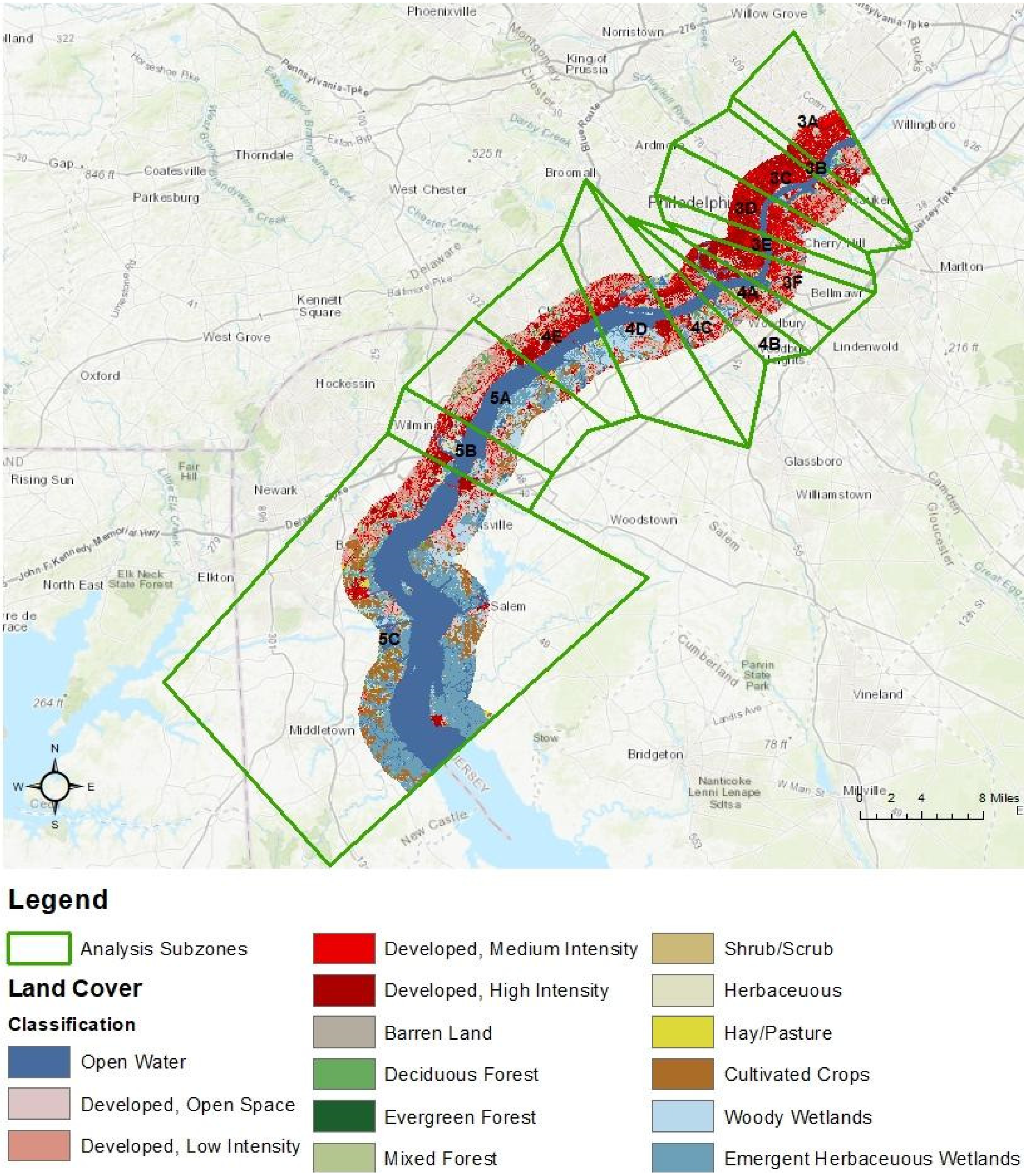
City	Length of Residence (years)
Philadelphia	16
Camden	17
Chester	21
Wilmington	17

Note. Data for average length of residence is from the U.S. Census Bureau (2020c).

Calculations

Results from Netusil, Kincaid, & Chang (2014) indicate that a 1 mg/L increase in dissolved oxygen levels contributed to increased sale prices for properties in two urban watersheds—the Burnt Bridge Creek watershed in Washington and the Johnson Creek watershed in Oregon (Table 5). The Burnt Bridge Creek watershed is more urbanized, with 94.6% of land cover classified as urban land, compared to only 66% urban cover in the Johnson Creek watershed.

Figure D2. Land Cover Distribution in the Study Region Within Two Miles of the Delaware River



Note. Land cover data from the Multi-Resolution Land Characterization (MRLC) Consortium (n.d.).

Urban land cover varies across our study subzones (Figure D2). Not including the area of the Delaware River within the subzone, subzones 3A to 4A have 80% or more of land cover categorized as urban land

and subzones 3F to 5C have 79% or less. We presume that subzones 3A to 4A could experience similar sale price increases as the Burnt Bridge Creek watershed and subzones 4B to 5C could experience increases similar to the Johnson Creek watershed.

Based on the estimates of dissolved oxygen distributions, a different set of subzones will gain a 1 mg/L or greater improvement in dissolved oxygen under the two restoration scenarios (Table D10, see also Appendix A.

Table D10. Predicted Change in Dissolved Oxygen Under the Full and Moderate Restoration Scenarios, Including Subzones Predicted to Gain a 1 mg/L or Greater D.O. Improvement

Zone	Full Restoration			Moderate Restoration		
	Event (mg/L)	Low (mg/L)	Typical (mg/L)	Event (mg/L)	Low (mg/L)	Typical (mg/L)
3A	1.10	0.90	0.65	0.95	0.80	0.55
3B	1.45	1.20	1.00	1.20	0.95	0.80
3C	1.85	1.50	1.35	1.45	1.15	1.05
3D	2.20	1.80	1.70	1.70	1.30	1.30
3E	2.20	1.80	1.70	1.70	1.30	1.30
3F	2.35	1.95	1.85	1.85	1.45	1.45
4A	2.50	2.10	2.00	2.00	1.60	1.60
4B	2.50	2.10	2.00	2.00	1.60	1.60
4C	2.35	1.95	1.85	1.85	1.45	1.45
4D	2.20	1.80	1.70	1.70	1.30	1.30
4E	1.60	1.30	1.40	1.10	0.80[a]	1.00
5A	1.40	0.75	1.10	1.20	0.55	0.80
5B	1.35	0.60	0.90	1.25	0.50	0.70
5C	1.30	0.40	0.20	1.30	0.40	0.10

[a] Under the “Low” condition, the predicted D.O. change in subzone 4E falls slightly below the 1.0 mg/L threshold (0.8 mg/L) (see Appendix A). Because the predicted D.O. change exceeds this threshold both for “Event” and “Typical” conditions in this subzone, as for upstream subzones in the “Low” distribution, 4E is included in the predicted benefit from water quality improvements to maintain continuity in the forecasts.

Potential property value gains for the Full and Moderate Restoration scenarios by zone of influence for urban and less urban subzones are calculated by the following equation (Tables D11 and D12):

> Potential Property Value Gain (2018$) = Estimated Effect on Property Sale Prices from a 1mg/L increase in Dissolved Oxygen (%) x Total Existing Property Value (2018$)

Where:

- Estimated Effect on Property Sale Prices from a 1 mg/L increase in Dissolved Oxygen (%) = Estimates in Table 5
- Total Existing Property Value (2018$) = Number of owner-occupied single-family units by tract (for subzones with ≥ 1 mg/L improvement in D.O.) x Median housing value by tract (2018$)

Table D11. Potential Property Value Gains for the Full Restoration Scenario by Zone of Influence

Zone of Influence	Total Existing Property Value (millions of 2018$)	Estimated Property Value Gain (millions of 2018$)	Average Property Value Gain per Residence (2018$)
Event			
0-1/4 mile (URBAN)	$843.5	$0	$0
0-1/4 mile (LESS URBAN)	$557.1	$76.4	$24,312
1/4-1/2 mile (URBAN)	$1,929.3	$86.6	$9,508
1/4-1/2 mile (LESS URBAN)	$588.4	$41.5	$12,226
1/2 - 1 mile (URBAN)	$4,284.4	$126.4	$4,993
1/2 - 1 mile (LESS URBAN)	$1,567.9	$128.3	$13,994
1-2 mile (URBAN)	$9,054.0	$287.0	$5,191
1-2 mile (LESS URBAN)	$5,840.5	$182.2	$5,997
Low			
0-1/4 mile (URBAN)	$706.5	$0	$0
0-1/4 mile (LESS URBAN)	$176.5	$24.2	$19,209
1/4-1/2 mile (URBAN)	$1,694.8	$76.1	$10,590
1/4-1/2 mile (LESS URBAN)	$168.4	$11.9	$9,177
1/2 - 1 mile (URBAN)	$3,541.6	$104.5	$5,493
1/2 - 1 mile (LESS URBAN)	$453.2	$37.1	$10,139
1-2 mile (URBAN)	$7,144.2	$226.5	$5,431
1-2 mile (LESS URBAN)	$2,446.2	$76.3	$5,236
Typical			
0-1/4 mile (URBAN)	$706.5	$0	$0
0-1/4 mile (LESS URBAN)	$290.4	$39.8	$22,287
1/4-1/2 mile (URBAN)	$1,694.8	$76.1	$10,590
1/4-1/2 mile (LESS URBAN)	$317.1	$22.4	$11,224
1/2 - 1 mile (URBAN)	$3,541.6	$104.5	$5,493
1/2 - 1 mile (LESS URBAN)	$948.4	$77.6	$13,095
1-2 mile (URBAN)	$7,144.2	$226.5	$5,431
1-2 mile (LESS URBAN)	$3,837.6	$119.7	$6,079

Table D12. Potential Property Value Gains for the Moderate Restoration Scenario by Zone of Influence

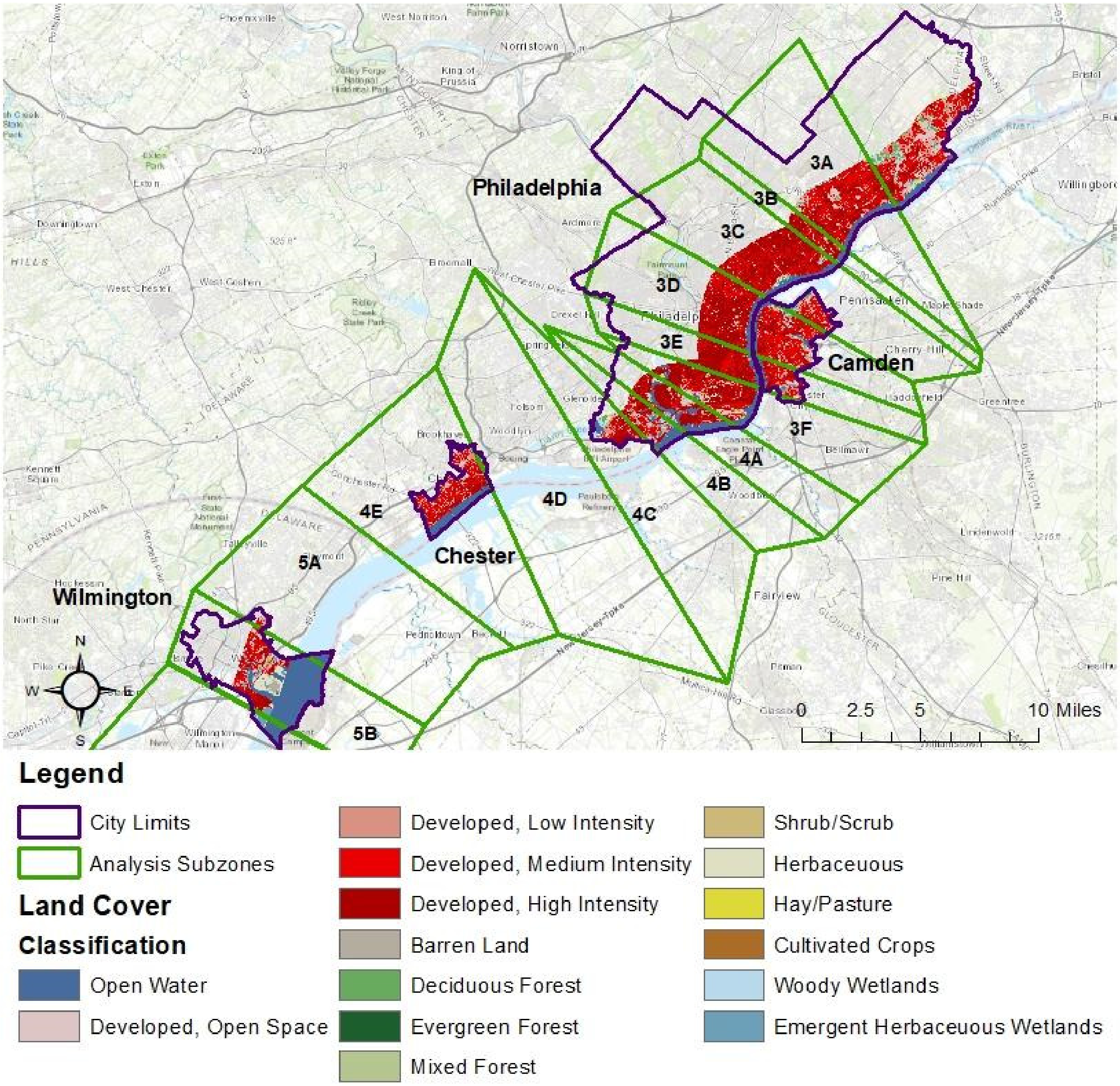
Zone of Influence	Total Existing Property Value (millions of 2018$)	Estimated Property Value Gain (millions of 2018$)	Average Property Value Gain per Residence (2018$)
Event			
0-1/4 mile (URBAN)	$706.5	$0	$0
0-1/4 mile (LESS URBAN)	$557.1	$76.4	$24,312
1/4-1/2 mile (URBAN)	$1,694.8	$76.1	$10,590
1/4-1/2 mile (LESS URBAN)	$588.4	$41.5	$12,226
1/2 - 1 mile (URBAN)	$3,541.6	$104.5	$5,493
1/2 - 1 mile (LESS URBAN)	$1,567.9	$128.3	$13,994
1-2 mile (URBAN)	$7,144.2	$226.5	$5,431
1-2 mile (LESS URBAN)	$5,840.5	$182.2	$5,997
Low[a]			
0-1/4 mile (URBAN)	$667.0	$0	$0
0-1/4 mile (LESS URBAN)	$176.5	$24.2	$19,209
1/4-1/2 mile (URBAN)	$1,637.4	$73.5	$10,829
1/4-1/2 mile (LESS URBAN)	$168.4	$11.9	$9,177
1/2 - 1 mile (URBAN)	$3,415.8	$100.8	$5,572
1/2 - 1 mile (LESS URBAN)	$453.2	$37.1	$10,139
1-2 mile (URBAN)	$6,848.9	$217.1	$5,543
1-2 mile (LESS URBAN)	$2,446.2	$76.3	$5,236
Typical			
0-1/4 mile (URBAN)	$667.0	$0	$0
0-1/4 mile (LESS URBAN)	$176.5	$24.2	$19,209
1/4-1/2 mile (URBAN)	$1,637.4	$73.5	$10,829
1/4-1/2 mile (LESS URBAN)	$168.4	$11.9	$9,177
1/2 - 1 mile (URBAN)	$3,415.8	$100.8	$5,572
1/2 - 1 mile (LESS URBAN)	$453.2	$37.1	$10,139
1-2 mile (URBAN)	$6,848.9	$217.1	$5,543
1-2 mile (LESS URBAN)	$2,446.2	$76.3	$5,236

[a] Under the "Low" condition, the predicted D.O. change in subzone 4E falls slightly below the 1.0 mg/L threshold (0.8 mg/L) (see Appendix A). Because the predicted D.O. change exceeds this threshold both for "Event" and "Typical" conditions in this subzone, as for upstream subzones in the "Low" distribution, 4E is included in the predicted benefit from water quality improvements to maintain continuity in the forecasts.

Urban Cities

We also calculate potential property value gains for single-family residential units two miles from the Delaware River within the city limits of Philadelphia, Camden, Chester, and Wilmington. These cities contain pockets of poverty which are most prevalent near the most degraded portions of the Delaware River (see "Environmental Justice Considerations"). Urban land cover accounts for 93% of total land cover in Philadelphia, 93% in Camden, 96% in Chester, and 66% in Wilmington (Figure D3).

Figure D3. Land Cover Distribution Within Two Miles of the Delaware River in the City Limits of Philadelphia, Camden, Chester, and Wilmington



Note. Land cover data from Multi-Resolution Land Characterization (MRLC) Consortium (n.d.)

Based on Netusil, Kincaid, & Chang (2014), Philadelphia, Camden, and Chester could experience increases like the more urban Burnt Bridge Creek watershed while Wilmington may see gains similar to the Johnson Creek watershed.[41] Tables D13 and D14 show the potential property value gains in Philadelphia, Camden, Chester, and Wilmington aggregated across subzones for the Full and Moderate Restoration scenarios.

Table D13. Potential Property Value Gains for the Full Restoration Scenario by City and Zone of Influence

Zone of Influence by City	Number of Properties	Total Existing Property Value (millions of 2018$)	Estimated Property Value Gain (millions of 2018$)	Average Property Value Gain per Residence (2018$)
Event				
Philadelphia (Urban)				
0-1/4 mile	1,949	$587.0	$0	$0
1/4-1/2 mile	7,339	$1,712.5	$76.9	$10,478
1/2 - 1 mile	19,869	$3,596.1	$106.1	$5,339
1-2 mile	40,825	$6,853.3	$217.2	$5,321
Camden (Urban)				
0-1/4 mile	570	$53.7	$0	$0
1/4-1/2 mile	710	$63.3	$2.8	$4,005
1/2 - 1 mile	2,326	$195.5	$5.8	$2,479
1-2 mile	3,236	$274.3	$8.7	$2,687
Chester (Urban)				
0-1/4 mile	186	$12.0	$0.0	$0
1/4-1/2 mile	306	$17.5	$0.8	$2,568
1/2 - 1 mile	1,241	$73.5	$2.2	$1,748
1-2 mile	1,374	$122.1	$3.9	$2,817
Wilmington (Less Urban)				
0-1/4 mile	26	$4.3	$0.6	$22,509
1/4-1/2 mile	24	$3.9	$0.3	$11,580
1/2 - 1 mile	35	$5.7	$0.5	$13,438
1-2 mile	1,927	$255.0	$8.0	$4,129

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[41] Because a portion of the Delaware River is incorporated within the city boundaries, we do not include land cover classified as “open water” in the total.

Table D13, Continued

Zone of Influence by City	Number of Properties	Total Existing Property Value (millions of 2018$)	Estimated Property Value Gain (millions of 2018$)	Average Property Value Gain per Residence (2018$)
Low				
Philadelphia (Urban)				
0-1/4 mile	1,599	$540.3	$0	$0
1/4-1/2 mile	5,660	$1,524.2	$68.4	$12,091
1/2 - 1 mile	14,406	$3,011.3	$88.8	$6,166
1-2 mile	29,066	$5,327.4	$168.9	$5,810
Camden (Urban)				
0-1/4 mile	570	$53.7	$0	$0
1/4-1/2 mile	710	$63.3	$2.8	$4,005
1/2 - 1 mile	2,326	$195.5	$5.8	$2,479
1-2 mile	3,236	$274.3	$8.7	$2,687
Chester (Urban)				
0-1/4 mile	186	$12.0	$0	$0
1/4-1/2 mile	306	$17.5	$0.8	$2,568
1/2 - 1 mile	1,241	$73.5	$2.2	$1,748
1-2 mile	1,374	$122.1	$3.9	$2,817
Wilmington (Less Urban)				
0-1/4 mile	0	$0	$0	$0
1/4-1/2 mile	0	$0	$0	$0
1/2 - 1 mile	0	$0	$0	$0
1-2 mile	0	$0	$0	$0
Typical				
Philadelphia (Urban)				
0-1/4 mile	1,599	$540.3	$0	$0
1/4-1/2 mile	5,660	$1,524.2	$68.4	$12,091
1/2 - 1 mile	14,406	$3,011.3	$88.8	$6,166
1-2 mile	29,066	$5,327.4	$168.9	$5,810
Camden (Urban)				
0-1/4 mile	570	$53.7	$0	$0
1/4-1/2 mile	710	$63.3	$2.8	$4,005
1/2 - 1 mile	2,326	$195.5	$5.8	$2,479
1-2 mile	3,236	$274.3	$8.7	$2,687

Table D13, Continued

Zone of Influence by City	Number of Properties	Total Existing Property Value (millions of 2018$)	Estimated Property Value Gain (millions of 2018$)	Average Property Value Gain per Residence (2018$)
Chester (Urban)				
0-1/4 mile	186	$12.0	$0	$0
1/4-1/2 mile	306	$17.5	$0.8	$2,568
1/2 - 1 mile	1,241	$73.5	$2.2	$1,748
1-2 mile	1,374	$122.1	$3.9	$2,817
Wilmington (Less Urban)				
0-1/4 mile[a]	0	$0	$0	$0
1/4-1/2 mile	0	$0	$0	$0
1/2 - 1 mile	0	$0	$0	$0
1-2 mile	402	$70.5	$2.2	$5,477

[a] Only a small portion of a home (.01) was counted in this zone of influence. The total existing property value for this fraction of a home was $2,093 (2018$), and the estimated property value gain totaled $287.

Table D14. Potential Property Value Gains for the Moderate Restoration Scenario by City and Zone of Influence

Zone of Influence by City	Number of Properties	Total Existing Property Value (millions of 2018$)	Estimated Property Value Gain (millions of 2018$)	Average Property Value Gain per Residence (2018$)
Event				
Philadelphia (Urban)				
0-1/4 mile	1,599	$540.3	$0	$0
1/4-1/2 mile	5,660	$1,524.2	$68.4	$12,091
1/2 - 1 mile	14,406	$3,011.3	$88.8	$6,166
1-2 mile	29,066	$5,327.4	$168.9	$5,810
Camden (Urban)				
0-1/4 mile	570	$53.7	$0	$0
1/4-1/2 mile	710	$63.3	$2.8	$4,005
1/2 - 1 mile	2,326	$195.5	$5.8	$2,479
1-2 mile	3,236	$274.3	$8.7	$2,687
Chester (Urban)				
0-1/4 mile	186	$12.0	$0	$0
1/4-1/2 mile	306	$17.5	$0.8	$2,568
1/2 - 1 mile	1,241	$73.5	$2.2	$1,748
1-2 mile	1,374	$122.1	$3.9	$2,817

Table D14, Continued

Zone of Influence by City	Number of Properties	Total Existing Property Value (millions of 2018$)	Estimated Property Value Gain (millions of 2018$)	Average Property Value Gain per Residence (2018$)
Wilmington (Less Urban)				
0-1/4 mile	26	$4.3	$0.6	$22,509
1/4-1/2 mile	24	$3.9	$0.3	$11,580
1/2 - 1 mile	35	$5.7	$0.5	$13,438
1-2 mile	1,927	$255.0	$8.0	$4,129
Low				
Philadelphia (Urban)				
0-1/4 mile	1,360	$505.5	$0	$0
1/4-1/2 mile	5,301	$1,471.4	$66.1	$12,462
1/2 - 1 mile	13,541	$2,894.5	$85.4	$6,306
1-2 mile	27,012	$5,113.1	$162.1	$6,001
Camden (Urban)				
0-1/4 mile	570	$53.7	$0	$0
1/4-1/2 mile	710	$63.3	$2.8	$4,005
1/2 - 1 mile	2,326	$195.5	$5.8	$2,479
1-2 mile	3,236	$274.3	$8.7	$2,687
Chester (Urban)[a]				
0-1/4 mile	186	$12.0	$0	$0
1/4-1/2 mile	306	$17.5	$0.8	$2,568
1/2 - 1 mile	1,241	$73.5	$2.2	$1,748
1-2 mile	1,374	$122.1	$3.9	$2,817
Wilmington (Less Urban)				
0-1/4 mile	0	$0	$0	$0
1/4-1/2 mile	0	$0	$0	$0
1/2 - 1 mile	0	$0	$0	$0
1-2 mile	0	$0	$0	$0
Typical				
Philadelphia (Urban)				
0-1/4 mile	1,360	$505.5	$0	$0
1/4-1/2 mile	5,301	$1,471.4	$66.1	$12,462
1/2 - 1 mile	13,541	$2,894.5	$85.4	$6,306
1-2 mile	27,012	$5,113.1	$162.1	$6,001

Table D14, Continued

Zone of Influence by City	Number of Properties	Total Existing Property Value (millions of 2018$)	Estimated Property Value Gain (millions of 2018$)	Average Property Value Gain per Residence (2018$)
Camden (Urban)				
0-1/4 mile	570	$53.7	$0	$0
1/4-1/2 mile	710	$63.3	$2.8	$4,005
1/2 - 1 mile	2,326	$195.5	$5.8	$2,479
1-2 mile	3,236	$274.3	$8.7	$2,687
Chester (Urban)				
0-1/4 mile	186	$12.0	$0	$0
1/4-1/2 mile	306	$17.5	$0.8	$2,568
1/2 - 1 mile	1,241	$73.5	$2.2	$1,748
1-2 mile	1,374	$122.1	$3.9	$2,817
Wilmington (Less Urban)				
0-1/4 mile	0	$0	$0	$0
1/4-1/2 mile	0	$0	$0	$0
1/2 - 1 mile	0	$0	$0	$0
1-2 mile	0	$0	$0	$0

[a] Under the "Low" condition, the predicted D.O. change falls slightly below the 1.0 mg/L threshold (0.8 mg/L) in the subzone Chester is located in (see Appendix A). Because the predicted D.O. change exceeds this threshold both for "Event" and "Typical" conditions here in Chester as well as for upstream subzones in the "Low" distribution, Chester is included in the predicted benefit from water quality improvements to maintain continuity in the forecasts.

Limitations

Because our study does not predict when a property within a particular zone of influence will sell, we instead present the value of potential property value gains if all properties were to be sold at some point in the future and the average expected gain per residence.

Our estimate of property value gains is conservative for three reasons. First, it is a partial estimate of total property value gains since it represents potential sale price increases for just one-unit owner-occupied households; additional real estate value increases from commercial or rental residential properties would add to this total. Second, our estimate relies on the results from Netusil et al. (2014), in which sale price increases are tied to a 1 mg/L improvement in dissolved oxygen levels. Properties in subzones with predicted D.O. gains close to but below the 1 mg/L threshold are conservatively assumed to not experience any sale price increase. Similarly, subzones experiencing a greater than 1 mg/L improvement in dissolved oxygen may have underestimated property value benefits, as we could expect that properties gaining more than a 1 mg/L improvement may see higher sale price increases than those with a 1 mg/L improvement. Property value benefits are likely to occur throughout a range of D.O.

improvements, with some benefits experienced below the 1 mg/L improvement threshold and greater benefits corresponding to higher increases in dissolved oxygen levels.

Third, Netusil et al. (2014) found no value gains in their more urban setting within a quarter-mile of the waterbody. While this could hold true for our setting, we hypothesize that gains in more urban settings within a quarter-mile of the river may be significant given the underlying political and ecological history of conditions in the Delaware Estuary. Indeed, Walsh et al. (2017) found that water clarity improvements, an indicator for water quality, in the neighboring Chesapeake Bay had statistically significant property value benefits for properties closest to the waterbody. Similarly, Bin & Czajkowski (2013) determined that increases in dissolved oxygen levels on coastal waterways in South Florida contributed to increases in waterfront property prices. The results from Walsh et al. (2012), which examined how water clarity improvements in Orange County, Florida's, lakes contributed to waterfront property value benefits, further echo this trend. Adding non-zero benefits within a quarter-mile of the Delaware Estuary would increase our overall valuation of property value changes.

There currently is a dearth of literature and hedonic price models specifically examining the relationship between dissolved oxygen, the spatial extent of property value benefits, and the shape of the benefit gradient across different markets and in tidal estuarine settings (Walsh et al., 2017). Netusil et al. (2014) does examine these relationships but in an urban river watershed setting. In lieu of more specific literature that would allow us to quantify property value benefits within a tidal estuarine setting, and because the watersheds in the Delaware Estuary are largely comprised of urban land cover, we apply the results of Netusil et al. (2014). More sophisticated models addressing the notion of scaled property value benefits related to varying levels of D.O. improvement within tidal estuarine settings would lead to a more refined overall valuation of benefits.

For the analysis on the distribution of property value gains across Philadelphia, Camden, Chester, and Wilmington, the variance in gains among the cities is due to differences in counts of and median property value of owner-occupied residential properties as well as which properties are set to gain property value from the 1 mg/L threshold. Aggregating data by zone of influence into one-mile zones (Table D15) allows us to examine why Philadelphia is slated to gain far greater benefits than the other three cities.

In both Camden and Chester, the number of owner-occupied properties and the average median value of those properties is substantially less than in Philadelphia. The majority of properties within the two-mile zone of influence in Camden and one-mile zone in Chester are renter-occupied (Table D15). Given that there are fewer owner-occupied properties with a lower median value relative to Philadelphia, and that properties within the zero to quarter mile zone of more urban areas are not predicted to receive benefits, the benefits in Camden and Chester will undoubtedly be lower using our methods of analysis. Not only will they be underestimated, but they also need to be understood in context. Hedonic price regression models and cost benefit analyses do not fully account for the distribution of environmental injustices, and how property value benefits could contribute more holistically to a dismantling of the environmental injustices in these historically economically underserved communities.

In Wilmington, there are a different set of anomalous issues to consider for context. Within the city limits (almost exclusively contained in subzone 5B), our predicted dissolved oxygen improvements have Wilmington only crossing the 1 mg/L threshold in the Full and Moderate restoration "event" conditions[42]; no benefits are predicted under "low" and "typical" conditions in our analyses. If the supporting literature allowed us to estimate property value benefits based on a continuous scale of dissolved oxygen improvements, the estimated gains would not be zero. Wilmington also has the fewest total number of owner-occupied properties compared to the other three cities (Table D15), in part because of the industrial waterfront along the Delaware River which dominates our analysis of the Wilmington response. Although Wilmington has comparable median property values to Philadelphia, there are fewer total properties and the properties closest to the river consist of more renter-occupied units.

Table D15. Total Number of Owner-Occupied Single-Family Properties, Average Median Value of Owner-Occupied Units, and Average Owner-Occupancy Rate within 2-Miles of Philadelphia, Camden, Chester, and Wilmington's City Limits

City	0-1 mile			1-2 mile		
	One Unit Owner-Occupied Properties	Average Value (2018$)	Average Owner-Occupancy Rate	One Unit Owner-Occupied Properties	Average Value of (2018$)	Average Owner-Occupancy Rate
Philadelphia	29,157	$238,510	58%	40,825	$167,869	51%
Camden	3,606	$89,145	39%	3,236	$84,759	46%
Chester	1,733	$60,249	46%	1,374	$88,874	54%
Wilmington	85	$164,240	44%	1,927	$132,353	52%

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[42] There are households under the Full Restoration typical condition that are predicted to receive benefits as well, however, we will primarily use subzone 5B for the general discussion of variance in Wilmington's property value benefit context.

Appendix E: Water Quality Improvement Interviews

We interviewed eight different individuals from organizations within the Delaware Estuary. The interviewee's positions, organization, and city of business can be found in Table E1. We asked each interviewee general questions about their respective communities, questions related to the project, and specific questions about their engagement in the estuary.

Table E1. Interviewees Information

Interviewee Position	Organization	City
Semi-Retired	Tookany/Tacony-Frankford Watershed Partnership	North Philadelphia
Executive Director	Shade Tree Commission	Chester
Deputy Director	Chester Economic Development Authority	Chester
Urban Farmer and Educator	Camden Center for Environmental Transformation	Camden (Waterfront South)
Executive Director	Riverfront North Partnership	Philadelphia
Environmental Education Program Director	Urban Promise	Camden
River Programs Manager and Support Staff	Bartram Gardens	Southwest Philadelphia
Assistant Director of Education	Kalmar Nyckel	Wilmington (Christina River)

Water Quality Interview Questions

1) Broadly, what are the biggest economic challenges your community currently faces? (e.g., education issues, health costs, etc.)
2) What about environmental? (air pollution, health of the Delaware River and surrounding creeks or tributaries, water quality, etc.)
3) How familiar/involved/engaged do you think residents in your community are with environmental issues?
4) Do you think environmental justice is an issue in your community?
5) How do you think residents in your community would rate the water quality of the Delaware River and associated creeks/surface water ways: poor, below average, average, above average, or excellent?
6) Building off the previous question (5), what drives residents in your community to that conclusion—either that the river's and associated creeks/surface water ways water quality hinders residents or draws residents in? (For example, perceptions about the river's appearance or cleanliness, "unsafe"/unable to swim in the river, unhealthy fish populations)

7) If no mention of perception issues: What are residents' perceptions of the Delaware River's and associated creeks/surface water ways water quality? (may be tied into previous question)
8) How do residents in your community currently use the Delaware River, streams, and creeks, if they use the river at all? For example, fishing, kayaking, other recreation, walks along the river, enjoy because of aesthetics, etc.
9) Do you think residents in your community would be more inclined to use the Delaware River, streams, and creeks, if water quality improved, or do other economic/environmental challenges take precedence in concern?
10) Have you visited the Delaware River, streams, and creeks in the last 12 months for a specific purpose (e.g., boating, birdwatching, fishing, walking)?
11) If yes (Q 10), how many times? (estimate)
12) If yes (Q 10), for what activities?
13) Do you think the water quality is sufficiently acceptable for participating in those recreational activities?
14) If water quality is not acceptable, what is the main reason for your opinion of water quality? (perception, trash, pollution)
15) Would you visit the Delaware River, streams, and creeks more if water quality improved?