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A Pathway for Continued Restoration: Improving Dissolved Oxygen in the Delaware River Estuary

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FINAL REPORT

Managing, Protecting and Improving the Water Resources of the Delaware River Basin since 1961

Delaware River Basin Commission
DELAWARE • NEW JERSEY
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UNITED STATES OF AMERICA

A PATHWAY FOR CONTINUED RESTORATION: IMPROVING DISSOLVED OXYGEN IN THE DELAWARE RIVER ESTUARY

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- Members of the DRBC Water Quality Advisory Committee.
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EXECUTIVE SUMMARY

At the time the Delaware River Basin Commission (DRBC or Commission) was created in 1961, for periods of up to six months each year, little or no dissolved oxygen (DO) was present in portions of the Delaware River Estuary ("the Estuary"), the tidal section of the Delaware River extending 133 miles from the head of tide at Trenton, New Jersey, to the mouth of Delaware Bay. Thanks in part to DRBC's regulation in 1968 of carbonaceous biochemical oxygen demand (CBOD; one of the major drivers of low dissolved oxygen in the river at that time) discharged by treatment plants, DO levels and fish populations in the Estuary have improved significantly over the decades since. Nonetheless, in the most urbanized reach of the Estuary, extending approximately 38 miles from Wilmington, Delaware, to just above the Tacony–Palmyra Bridge (which spans the Delaware River to connect Palmyra, New Jersey, and the Tacony section of Philadelphia, Pennsylvania), DO levels remain lower than in the regions both up- and downstream of this section. This condition, referred to as a "DO sag," is especially pronounced during periods of low flow during the summer months of July through September.

This report documents the DRBC's work under Resolution No. 2017-4, adopted September 13, 2017, and its continuation of that work following a shift in DRBC's regulatory role, under a Resolution for the Minutes adopted September 7, 2023. By Resolution No. 2017-4, the Commissioners instructed the staff to conduct a series of studies, in consultation with co-regulators and dischargers and consistent with the goals of the federal Clean Water Act, 33 U.S.C. § 1251 *et seq.*, to assess the potential to further control pollution and thereby improve dissolved oxygen in water quality Zones 3 and 4 and the upper portion of Zone 5, within which the DO sag occurs. The authors refer to this reach as the "Fish Maintenance Area" (FMA) because current water quality standards applicable within this area were designated to maintain fish populations but not to support fish propagation.

Under Resolution No. 2017-4, the staff's multi-disciplinary investigations were to culminate in a DRBC rulemaking for the adoption of new aquatic life use water quality standards, to include propagation, in the FMA. DRBC's initial draft of this report, *Analysis of Attainability: Improving Dissolved Oxygen and Aquatic Life Uses in the Delaware River Estuary* (DRBC, 2022a) thus sought in part to demonstrate that propagation would be supported by the highest attainable level of DO in the FMA, as a basis for rulemaking. That purpose shifted after the United States Environmental Protection Agency (EPA) Administrator in December 2022 determined that revised water quality standards were necessary under the Clean Water Act (CWA) and, as a consequence, that EPA must conduct a rulemaking of its own.[1] As a result of EPA's decision, the Commission in September 2023 suspended its actions to develop and promulgate revised aquatic life use water quality standards for the Estuary and announced that it would

[1] "… CWA Section 303(c)(4) requires that the Administrator promptly prepare and publish proposed regulations setting forth new or revised WQS following a Determination that new or revised WQS are necessary to meet the requirements of the CWA." Letter from Radhika Fox to Steven Tambini, Shawn M. Garvin, Shawn M. LaTourette, and Ramez Ziadeh (Dec. 1, 2022), p.11.

"continue to provide [the staff's] scientific, technical, and engineering assistance to support EPA's process for revising aquatic life designated uses and corresponding criteria for Water Quality Zones 3 and 4 and the upper portion of Zone 5 to attain and maintain propagation of aquatic life, consistent with the staff's best professional judgment and expertise." The Commission further committed to continuing its coordination and collaboration with state and federal co-regulators during the EPA's rulemaking process. It also promised to "work with the EPA, co-regulator states, and interested stakeholders through [DRBC's WQAC] to develop plans, analyses, and, if appropriate, related regulations for the implementation of [upgraded] aquatic life uses and criteria in the Delaware River Estuary."

In accordance with these new directives, this report, together with supporting studies, including those performed by the DRBC and those it commissioned, describes a pathway to significantly improving DO levels within the FMA. This study is purely technical and scientific in nature and does not propose regulatory measures or approaches. Nor does it provide a basis for alleviating regulatory requirements, such as those imposed by NPDES permits for implementing water quality standards. Key findings include that:

- The addition of technically feasible advanced treatment by nine major wastewater treatment plants discharging to the Estuary would significantly improve the level of DO that can be achieved in the FMA and would provide for the protection and propagation of fish and other aquatic life throughout the Estuary.[2]

- The capital, operations, and maintenance costs of advanced treatment, beyond which further investment towards nitrogen removal yields no further meaningful DO improvement in the FMA (referred to in this report as the "inflection point"), are significant. However, analyses using metrics developed by the EPA and by the utility industry (American Water Works Association [AWWA], National Association of Clean Water Agencies [NACWA], and Water Environment Federation [WEF]) indicate that the cost of adding such treatment will not increase the affordability burden category, as defined by either method, for households within the service areas of the affected treatment plants.

The restoration analysis presented in this document identifies those pollutant sources that impact DO in the FMA and, conversely, those that have no meaningful effect, such that removing them entirely would

[2] Citing DRBC's draft *Analysis of Attainability* report, the EPA has stated that the resultant DO conditions "would consistently provide for both the protection and propagation of even sensitive aquatic species." EPA Administrator's determination, expressed in Letter from Radhika Fox to Steven Tambini, Shawn M. Garvin, Shawn M. LaTourette, and Ramez Ziadeh (Dec. 1, 2022).

produce no significant[3] improvement in DO conditions. The analysis was conducted using a linked three-dimensional hydrodynamic and water quality model developed and calibrated by a DRBC team under the guidance of a panel of highly qualified experts. Multiple sensitivity and test scenario simulations were performed to identify the degree to which various sources have the potential to reduce the DO sag and to enhance overall DO conditions in the FMA. The Model Expert Panel fully endorsed the model and the staff's scenario results, technical findings, and model-related work products documented in this report.

DO conditions in the Delaware River Estuary are dynamic, varying both temporally and spatially. An initial and fundamental step in the Commission's analysis was developing a baseline simulation, or design condition, against which to compare alternate scenarios. The design condition was developed to reflect a "worst case" scenario. Although current bathymetry was assumed, environmental conditions for the year 2012 were used because that year saw the lowest Estuary DO conditions among the three years simulated and in fact the lowest DO in the twelve-year period from 2011 to 2022. Point source effluent characteristics were based on recent (2018–2019) data and were simulated at their permitted flow rates, reflecting maximum allowable wastewater loads. Staff developed multiple metrics to objectively compare scenarios and to communicate their attributes to stakeholders.

After the baseline DO condition for the entire Estuary was developed, DO sensitivity simulations for individual sources (e.g., individual tributaries and individual point source discharges), pollutants (e.g., ammonia and other nutrient forms) and source categories (e.g., point sources, tributaries, combined sewer overflows, direct runoff) were performed. Thirteen wastewater discharges out of the 67 included in the linked hydrodynamic and water quality model[4] were preliminarily identified as potentially impactful and manageable sources based on initial screening sensitivity tests. Sequential model simulations were used to evaluate the incremental and cumulative impacts of these wastewater discharges on DO in the Estuary. Through this process, nine wastewater discharges from among the thirteen were identified as contributing to low DO due to high ammonia nitrogen load in the FMA. Together, these nine wastewater discharges contribute 96 percent of the total ammonia nitrogen load discharged to the Estuary by wastewater treatment point sources.

Using the design condition as a baseline, eight point-source nitrogen reduction scenarios were developed and characterized in terms of resultant DO improvement, estuary-wide cost, and facility-specific affordability. Of the eight nitrogen reduction scenarios evaluated, the study identified scenario AA08 as representing the level of treatment and associated cost beyond which further treatment (and investment)

[3] "Significant" in this context is not meant to convey statistical significance. While the scenarios tested and metrics calculated are of course quantitative, scenarios were mostly compared qualitatively by viewing the metrics visually on graphs. When the metrics from two scenarios lie directly on top of one another using a reasonable scale, they are not meaningfully different, meaning any calculable differences would be very small compared to model and data uncertainties as well as biological sensitivities. The purpose was to isolate the factors that "move the needle" in terms of DO in the FMA and those that do not.

[4] The linked hydrodynamic and water quality model is hereafter referred to in this report as the "eutrophication" model, since it simulates processes such as photosynthesis and decomposition, which impact dissolved oxygen.

would yield no further discernable DO improvement—the inflection point or "knee-of-the-curve" with respect to DO improvements. This scenario includes: 1) reduction of effluent ammonia nitrogen to 1.5 mg/L by seven wastewater treatment plants[5] discharging within the FMA; and 2) reduction of effluent ammonia nitrogen to 5 mg/L by two wastewater treatment plants[6] discharging to locations upstream of the FMA, but which meaningfully impact DO in the FMA. Reductions in CBOD that would be expected to accompany wastewater treatment for nitrogen removal were incorporated into each nitrogen reduction scenario, including AA08.

A restoration scenario (AA15) based on scenario AA08 was developed, incorporating: 1) full implementation of combined sewer overflow (CSO) long-term control plans; 2) summer effluent DO concentrations of 4 mg/L for the nine discharges with reduced effluent ammonia levels; 3) assumed seasonal variations of ammonia effluent levels based upon expected treatment performance; and 4) a ten percent reserve capacity for future growth. The simulation results showed substantial DO improvement in the FMA relative to the baseline design condition. The minimum DO at the lowest point of the sag moved upstream by 10 miles (farther away from a known breeding area for the endangered Atlantic Sturgeon) and increased by approximately 2.3 mg/L, a biologically significant enhancement of the minimum DO conditions that typically occur between July and September. In addition, the length of the Delaware River reach with DO levels below 5.0 mg/L was predicted to decrease from about 51 miles under current conditions to about 12 miles under the restoration scenario described in this report.

Importantly, the design condition, upon which the restoration scenario is based, serves as a comparative tool to isolate those sources and loads that impact DO in the FMA, but the authors do not advance the condition as the basis for determining effluent limits or wasteload allocations. The levels of nitrogen reduction tested were based on cost and feasibility scenarios evaluated in a 2021 study performed for the Commission by Kleinfelder (DRBC, 2021). That analysis estimated the cost of effluent ammonia reductions from key point source dischargers using proven and available technologies. Neither the Kleinfelder study published in 2021 nor the DRBC restoration scenario described in this *Pathway for Continued Restoration* report was driven by a particular water quality endpoint, as would be the case for a study aimed at establishing wasteload allocations or determining effluent limits. Rather, the restoration scenario describes an FMA DO condition that is achievable under critical hydrologic and loading conditions. To determine whether and with what frequency a particular water quality endpoint is "attainable" in the regulatory sense of that word and assign wasteload allocations to point sources for achieving that

[5] The seven municipal wastewater treatment plants discharging within the FMA are the Philadelphia Water Department's Northeast Water Pollution Control Plant (PWD NE), Southeast Water Pollution Control Plant (PWD SE), and Southwest Water Pollution Control Plant (PWD SW), and plants operated by the Camden County Municipal Utilities Authority (CCMUA), Gloucester County Utility Authority (GCUA), Delaware County Regional Water Quality Control Authority (DELCORA), and City of Wilmington Wastewater Treatment Plant.

[6] The two wastewater treatment plants discharging within Zone 2, upstream of the FMA, are the Hamilton Township Water Pollution Control Facility and the plant operated by Lower Bucks County Joint Municipal Authority.

endpoint, it may be necessary to use a more representative[7] baseline, perform iterative sensitivity scenarios to identify those that satisfy a particular water quality target, and methodologically account for model uncertainty and limitations. When revised DO criteria are promulgated for the FMA, DRBC anticipates working with the Estuary states and the EPA to conduct a wasteload allocation study that could provide the basis for the states to impose effluent limits on dischargers to satisfy the new criteria.

Notably, model uncertainty can be magnified under different loading conditions at unobserved locations. After completing its initial analysis and publishing the results in the draft *Analysis of Attainability*, the authors addressed this limitation by developing a semi-empirical methodology for improving modeled DO estimates (Appendix A). The methodology leverages the eutrophication model's strengths in terms of characterizing relative changes from one scenario (or location) to another, as well as the availability of continuous reliable data at discrete locations within the Estuary, to improve estimates of baseline and restored DO at unmonitored locations. The result is a more reliable estimate of DO under the baseline and restoration scenarios throughout Zones 3 and 4, where the DO sag typically occurs, over the 15 years for which continuous data were analyzed.

The DRBC prepared four additional water quality simulations specifically for EPA's use in its rulemaking to revise the aquatic life use and supporting water quality criteria for DO in the FMA (Appendix D). These simulations incorporate minor adjustments to the baseline design condition and restoration scenario (AA15) described above.

[7] As noted above, the draft *Analysis of Attainability* report (DRBC, 2022a) defined the attainable use in the FMA as the level of propagation corresponding to the highest dissolved oxygen condition that could be demonstrated under conservative assumptions. Based in part on feedback received from its Water Quality Advisory Committee and in part due to the Commission's revised directive to staff of September 7, 2023, this restoration analysis does not address attainability directly, and it explores model uncertainty and inter-year variability to a greater degree (Appendix A).

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LIST OF ACRONYMS/ABBREVIATIONS

2D	two-dimensional (model)
3D	three-dimensional (model)
AA	analysis of attainability
AACE	American Association of Cost Estimating
AWWA	American Water Works Association
BAF	biological aerated filter
C	carbon
CBOD	carbonaceous biochemical oxygen demand (CBODU indicates ultimate CBOD)
CCMUA	Camden County Municipal Utilities Authority
C&D	Chesapeake and Delaware
cfs	cubic feet per second
CSO	combined sewer overflow
CWA	Clean Water Act
Δ	delta (difference)
DE	Delaware
DELCORA	Delaware County Regional Water Quality Control Authority
DO	dissolved oxygen
DRBC	Delaware River Basin Commission (or Commission)
EFDC	Environmental Fluid Dynamics Code
EPA	U.S. Environmental Protection Agency
ESA	Endangered Species Act
FMA	Fish Maintenance Area
GCUA	Gloucester County Utilities Authority
HA	Household Affordability metric
IFAS	integrated fixed film activated sludge
IQR	inter-quartile range
LBCJMA	Lower Bucks County Joint Municipal Authority
LTCP	long-term control plan
MA	municipal authority
MGD	million gallons per day
MS4	municipal separate storm sewer system

N	nitrogen
NACWA	National Association of Clean Water Agencies
NJ	New Jersey
NH34	ammonia-nitrogen (aka ammonia)
NO3	nitrate-nitrogen (aka nitrate)
NPDES	National Pollutant Discharge Elimination System
NPS	non–point source
O2	Oxygen
P	phosphorus
PA	Pennsylvania
PCBs	polychlorinated biphenyls
PWD	Philadelphia Water Department
RI	Residential Indicator metric
RM	river mile
RSI	Relative Stress Index metric
TMDL	total maximum daily load
TN	total nitrogen
WASP	Water Quality Analysis Simulation Program
WEF	Water Environment Federation
WPCF	water pollution control facility
WPCP	water pollution control plant
WQAC	Water Quality Advisory Committee
WWTP	wastewater treatment plant
USGS	U.S. Geological Survey
Zone	DRBC water quality management Zone

1. Background and Purpose

1.1 Historical Context

Fish, shellfish, and other forms of aquatic life rely on dissolved oxygen (DO), gaseous oxygen dissolved in water, to respire (breathe), making it among the most critical environmental parameters directly affecting aquatic life. Levels of DO in the tidal Delaware River from Philadelphia, Pennsylvania, to Wilmington, Delaware, have been impacted by human activity for more than 100 years. By the mid-1900s, pollution in the tidal river near Philadelphia and Camden, New Jersey, was so severe that from May to October, the Delaware River Estuary ("the Estuary") between Chester, Pennsylvania, and Philadelphia was typically anoxic (i.e., near-zero DO). In addition to rendering the urban portion of the river inhospitable to resident fish, these conditions prevented diadromous[8] fish species from passing through the Estuary to reproduce and from returning through the Estuary after spawning.

Persistently poor water quality in the tidal river was one of the key factors that drove the Estuary states, the State of New York, and the United States to enter into the Delaware River Basin Compact, the 1961 statute that created the Delaware River Basin Commission (DRBC or Commission). Relying on authority conferred by the Compact, the Commission undertook the tasks of establishing uses to be protected in Basin waters and adopting water quality criteria to define the pollutant levels or conditions necessary to protect those uses. The Commission divided the Delaware River Estuary[9] (Figure 1-1) into five water quality assessment and management Zones, numbered 2 through 6, each encompassing a portion of the mainstem and the tidal portions of the tributaries thereto, from the mouth of Delaware Bay between Cape Henlopen, Delaware, and Cape May, New Jersey (River Mile [RM] 0.0), to the head of tide at Trenton, New Jersey (RM 133.4). The Delaware River Estuary includes the tidal Delaware River (Zones 2 through 5) and Delaware Bay (Zone 6).

[8] Diadromous fish species migrate between salt water and fresh water; anadromous fish species live in the sea as adults and migrate into fresh water to spawn, whereas catadromous fish species live in fresh water as adults and migrate into salt water to spawn.

[9] The coastal water body where freshwater from rivers and streams mixes with salt water from the ocean is called an estuary. The estuary formed by the Delaware River, referred to interchangeably in this document as the "Delaware River Estuary," the "Delaware Estuary," or the "Estuary," consists of both a tidal river and a bay. The Delaware River Estuary therefore includes both the tidal Delaware River (Zones 2–5) and the Delaware Bay (Zone 6).

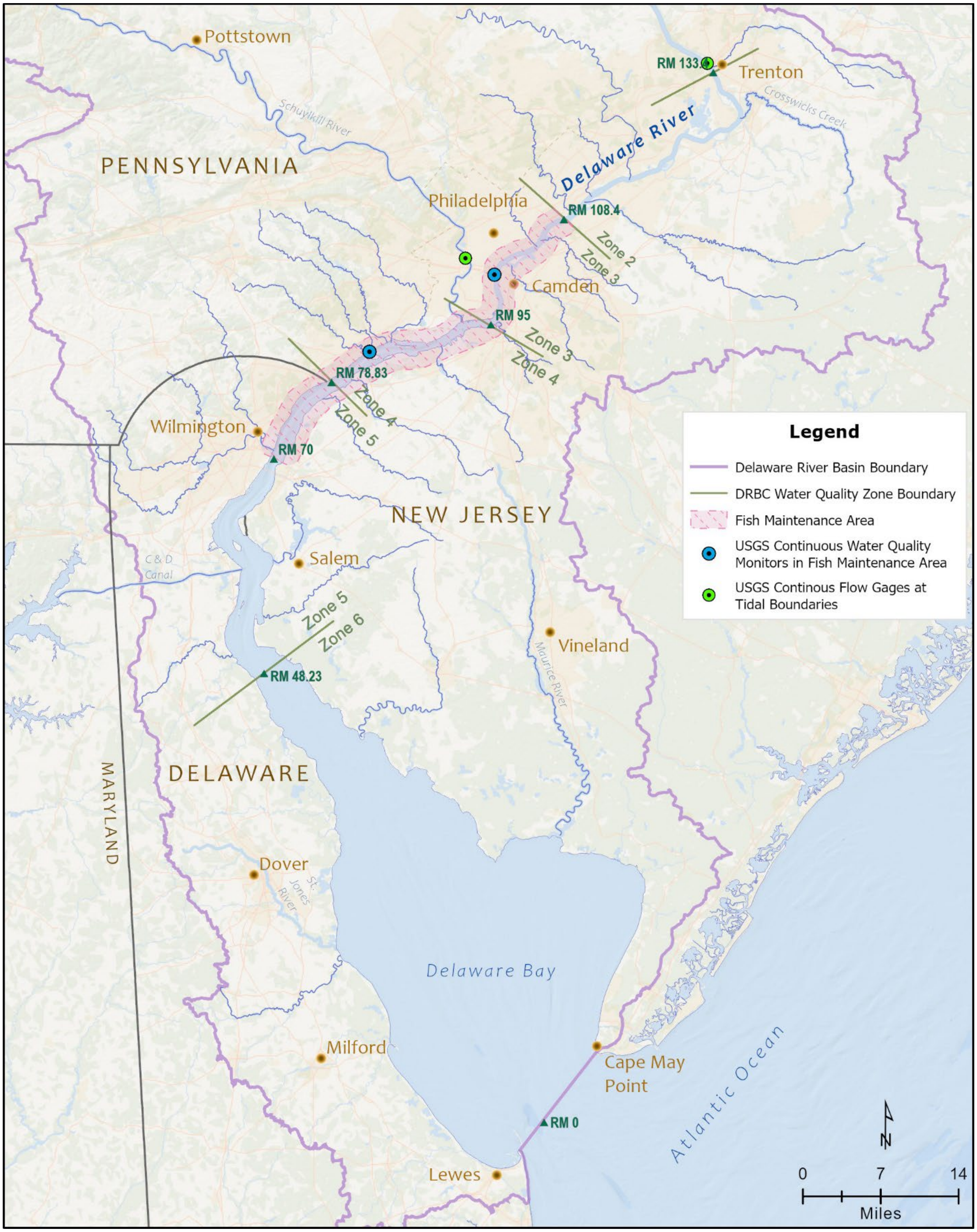


Figure 1-1: Delaware River Estuary

The Commission adopted designated uses and supporting water quality criteria (in DRBC parlance, "stream quality objectives") for the Estuary in 1967. Although uses and criteria supporting fish propagation were adopted for Zones 2, middle and lower Zone 5, and Zone 6, in recognition of "technical and financial challenges, the[] . . . standards included a compromise position for 38 miles of the 133-mile-long Estuary: a limited 'use' for Zones 3, 4, and upper Zone 5 that did not include 'propagation'[,] along with lower dissolved oxygen water quality criteria" (DRBC, 2015). These objectives were established with the understanding that they could be achieved through the allocation of wasteloads for carbonaceous biochemical oxygen demand (CBOD) among point source dischargers to the Estuary. The process was analogous to implementing a total maximum daily load (TMDL) under the Federal Water Pollution Control Act Amendments of 1972, commonly referred to as the Clean Water Act. Under the Clean Water Act and state laws, the Estuary states established designated uses and criteria for interstate waters, including the Estuary, by deferring or referring to DRBC's water quality standards.

By the late 1980s, with the assistance of federal grants provided under the Clean Water Act, significant new investment was made to improve municipal wastewater treatment facilities in the Delaware River Basin to control pollution loads and meet DRBC-directed wasteload allocations. As a result, DO levels in the Estuary steadily improved and now meet the established water quality criteria. Figure 1-2 shows daily-average DO during July and August from 1965–2022 based on continuous data collected at the Penn's Landing United States Geological Survey (USGS) station (previously called the Ben Franklin Bridge station[10]), compared with the 24-hour average DO criteria established in 1967. Each box[11] in the figure shows the central 50% of daily averages in July and August, with the horizontal line representing the median value. The recovery of DO in the Delaware Estuary over six decades has been extraordinary. As a result of this historic DO improvement, resident fish populations in this region of the Estuary, as well as migratory fish, have returned.

[10] Dissolved oxygen has been measured consistently at this general location (USGS 01467200) since October 1961, and water level measurements have been recorded here since 1949. The current monitoring location is 2,500 ft downstream from the Ben Franklin Bridge at Penn's Landing in Philadelphia. Prior to January 2020, this USGS monitoring station was called the Delaware River at Ben Franklin Bridge instead of its current name, the Delaware River at Penns Landing. The monitoring devices were located at the end of Pier 12 about 150 ft upstream of the Ben Franklin Bridge from July 1988 to December 2019. Prior to July 1988, they were located on the edge of Pier 11, about 300 ft downstream of Pier 12.

[11] The box and whisker plot is a graphical illustration of numerical data to show the distribution of data through their quartiles (box) and data ranges (whiskers and circles). This report employed the standard box and whisker plot definition to summarize the data spread. The structure of each box indicates the following: bottom edge of the box = the first quartile (Q1 or 25th percentile); mid-point line on the box = median (50th percentile); uppermost edge of the box = the third quartile (Q3 or 75th percentile); entirety of the box = interquartile range (IQR), the distance between Q3 and Q1. The whiskers are based on the IQR: the upper (lower) whisker is drawn to: 1) the largest (smallest) observed data point from the dataset if that point falls within a distance of 1.5 × the IQR above Q3 (below Q1); or 2) the full distance 1.5 × IQR above Q3 (below Q1), if the largest (smallest) observed data point falls beyond this distance. Any observed data points beyond the whisker boundaries are plotted as circles.

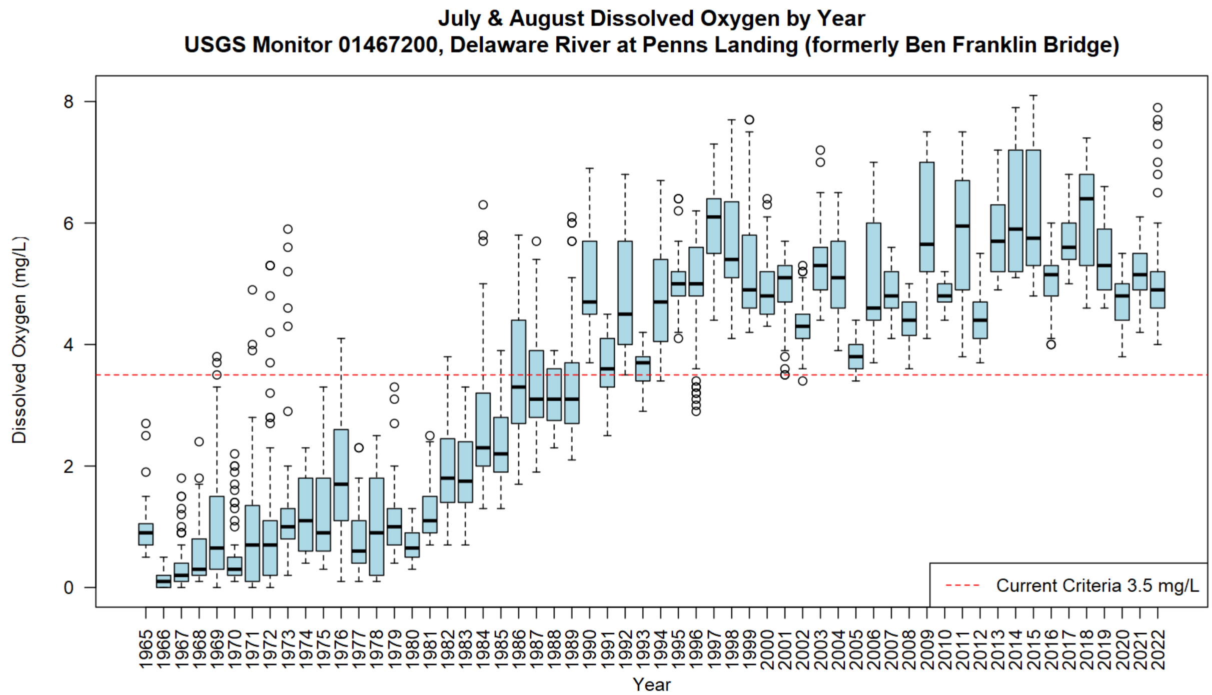
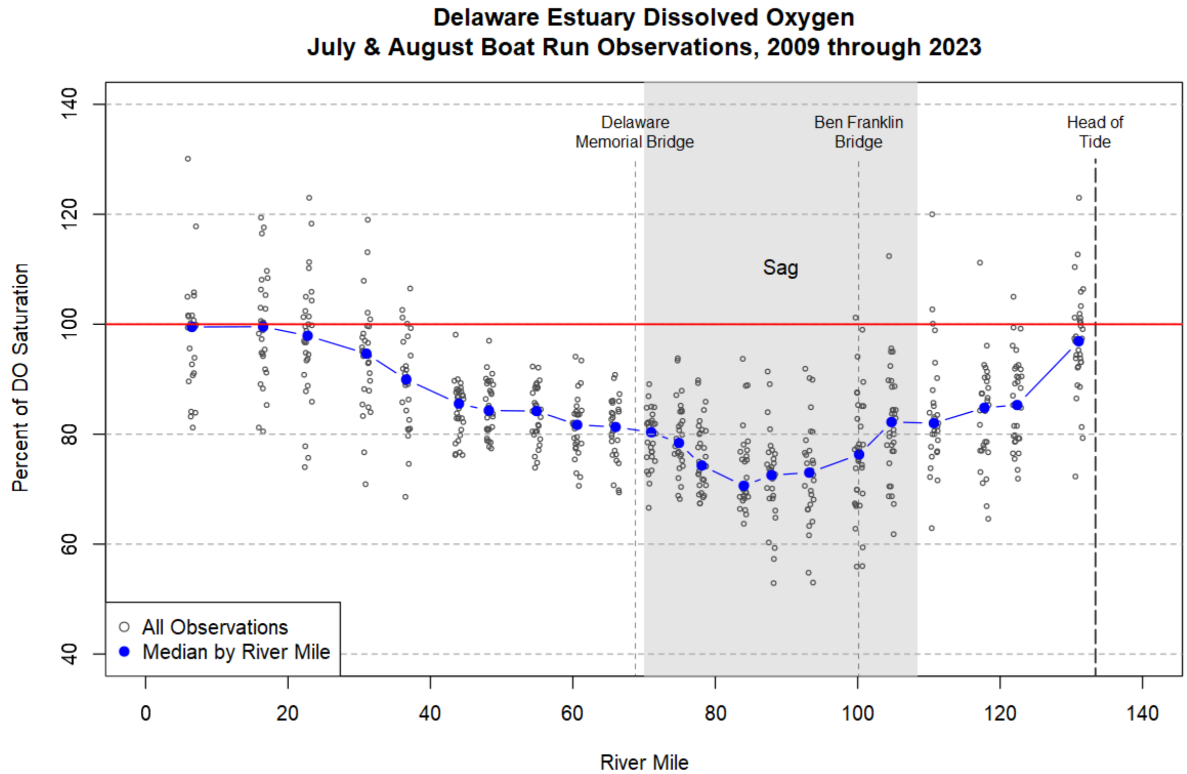


Figure 1-2: DO at Ben Franklin Bridge during July and August from 1965–2022

Nonetheless, dissolved oxygen in the densely urbanized portion of the Estuary, comprising Zones 3 and 4 and the upper portion of Zone 5, from RM 70 to 108.4, remains lower than in the Estuary regions up- and downstream. This condition, referred to as the "DO sag," is especially pronounced during periods of low flow during the summer months of July and August (Figure 1-3).

Following incomplete attempts to reevaluate designated aquatic life uses in the 1990s, and in response to a United States Environmental Protection Agency (EPA) initiative on nutrients, the Commission's Water Quality Advisory Committee (WQAC) in 2007 renewed efforts to evaluate nutrient and DO conditions in the Delaware Estuary. DRBC staff developed a Nutrient Criteria Plan (DRBC, 2013a) that includes components addressing DO criteria in the Estuary and nutrient criteria in both the non-tidal and tidal waters of the Delaware River. The initial focus of this plan was to ". . . address dissolved oxygen directly, particularly the direct effects on oxygen from BOD loading, and [to] include an evaluation of the uses currently falling below Clean Water Act goals." In Fall 2013, the WQAC recommended that staff evaluate the existing uses of Zones 3 and 4 and the upper portion of Zone 5 for propagation of resident and anadromous fish species.

That evaluation resulted in the report *Existing Use Evaluation for Zones 3, 4 & 5 of the Delaware Estuary Based upon Spawning and Rearing of Resident and Anadromous Fishes* (DRBC, 2015). While evidence of propagation was presented in the 2015 Report, the report concluded that "[f]ull attainment of a 'maintenance and propagation' use has not been demonstrated now based on the data available and examined for this existing use evaluation."



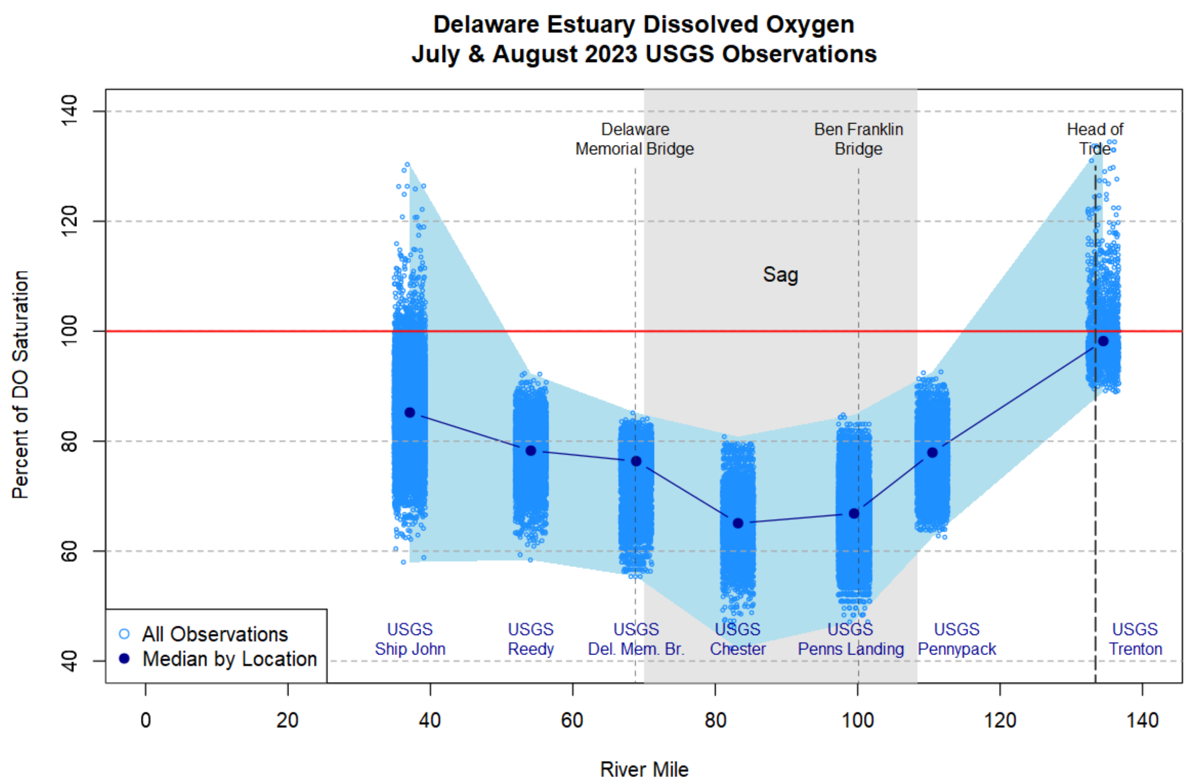


Figure 1-3: Dissolved oxygen "sag" in urban portion of the Delaware River Estuary

1.2 Regulatory Context

1.2.1 Existing Water Quality Standards

Each zone of the Delaware River Estuary has multiple designated uses and water quality criteria to support those uses. The water quality standards the Commission adopted in 1967 for aquatic life uses are summarized in Table 1-1 below. Propagation of resident fish is not a designated use for the 38-mile reach comprising Zones 3 and 4 and the upper portion of Zone 5, where the DO criterion is 3.5 mg/L as a 24-hour average. While the Commission and co-regulators recognized that this level of DO would not be sufficient to fully restore and protect aquatic life, the Commission adopted criteria deemed feasible at the time, based on the DRBC's engineering evaluation. Also based on that evaluation, the Commission assigned wasteload allocations for carbonaceous biochemical oxygen demand to Estuary point-source dischargers in 1968.

Table 1-1: Applicable aquatic life uses and DO criteria for the Delaware River Estuary[12]

Zone	River Mile	Aquatic Life Uses[1]	DO criteria[2]
2	108.4–133.4	Maintenance and propagation of resident fish and other aquatic life	24-hour average of 5.0 mg/L Seasonal average of 6.5 mg/L
3	95.0–108.4	Maintenance of resident fish and other aquatic life	24-hour average of 3.5 mg/L Seasonal average of 6.5 mg/L
4	78.8–95.0	Maintenance of resident fish and other aquatic life	24-hour average of 3.5 mg/L Seasonal average of 6.5 mg/L
5	70.0–78.8	Maintenance of resident fish and other aquatic life	24-hour average of 3.5 mg/L Seasonal average of 6.5 mg/L
	59.5–70.0	Maintenance and propagation of resident fish and other aquatic life	24-hour average of 4.5 mg/L Seasonal average of 6.5 mg/L
	48.2–59.5	Maintenance and propagation of resident fish and other aquatic life	24-hour average of 6.0 mg/L Seasonal average of 6.5 mg/L
6	0.0–48.2	Maintenance and propagation of resident fish and other aquatic life Maintenance and propagation of shellfish	24-hour average of 6.0 mg/L Not less than 5.0 mg/L at any time unless due to natural conditions

Notes: [1] Aquatic life uses for Zones 2–6 also include passage of anadromous fish and wildlife.

[2] For seasonal average DO criteria for Zones 2–5, the season is defined as "During periods from April 1 to June 15, and September 16 to December 31".

[12] Delaware River Basin Water Code (DRBC, 2013b)

In this report, Zone 3, Zone 4, and the upper portion of Zone 5 (RM 70–108.4), within which the current designated aquatic life use is "maintenance of resident fish and other aquatic life, passage of anadromous fish," are collectively referred to as the Fish Maintenance Area (FMA). The designated aquatic life use in Zone 2 and the remainder of Zone 5 is "maintenance *and propagation* of resident fish and other aquatic life, passage of anadromous fish" (emphasis added).

1.2.2 Resolution No. 2017-4

After reviewing the 2015 *Existing Use Evaluation* and considering input from the WQAC and Estuary co-regulators,[13] the Commission in 2017 unanimously adopted Resolution No. 2017-4.[14] That instrument recognized that the assembled evidence supported further study on the inclusion of propagation as a designated use in the FMA. Among other things, it directed the Commission to perform a series of studies as a foundation for upgrading the designated uses and water quality criteria required to support these uses in the FMA. The Commission thus recognized the importance of determining the appropriate aquatic life use designations and water quality criteria, while underscoring the importance of reaching these determinations through a collaborative process informed by technical studies and specialized scientific and engineering expertise.

Resolution No. 2017-4 recognized the Estuary's remarkable recovery from water quality conditions that for many decades prevented the successful reproduction of resident and anadromous fish such as the American Shad, Striped Bass, and Atlantic Sturgeon. It acknowledged the many activities and actors responsible for this achievement, including: efforts by state and federal agencies to implement and administer the Clean Water Act; construction and effective operation of wastewater treatment works by public entities and private industry; scientific work by regulatory agencies and academic institutions to document water quality improvements and the return of fish and other aquatic life; and public support for restoration and protection of the Delaware Estuary, a vital shared resource.

The technical studies enumerated by the Resolution are shown in Figure 1-4. They focus on: fish and DO relationships, data collection, development and calibration of a eutrophication (linked hydrodynamic and water quality) model, and social and economic impact factors affecting the attainment of uses. The Resolution also directed the DRBC staff to prepare an "analysis of attainability" (AA) report, synthesizing the findings and recommendations of each study.

DRBC completed or engaged others to complete each of the technical studies that Resolution No. 2017-4 directed the staff to perform. It did so in cooperation with the DRBC's state and federal co-regulators and

[13] The term "Estuary co-regulators" is used by the DRBC to refer to the regulatory apparatus of its member Estuary states (Delaware, New Jersey, and Pennsylvania) and Regions 2 and 3 of the EPA.

[14] DRBC, Resolution No. 2017-4 (Sept. 13, 2017), available at: https://www.state.nj.us/drbc/library/documents/Res2017-04_EstuaryExistingUse.pdf.

stakeholders, and with a high degree of transparency. Each phase of the Commission's monitoring, modeling, and analytical effort, including methodologies, assumptions, and management scenarios, was presented to DRBC's WQAC, on which dischargers, the scientific community, environmental groups, and co-regulators are represented. As noted above, model development benefited from the guidance of a panel of experts who concluded that the eutrophication model developed by DRBC staff is scientifically

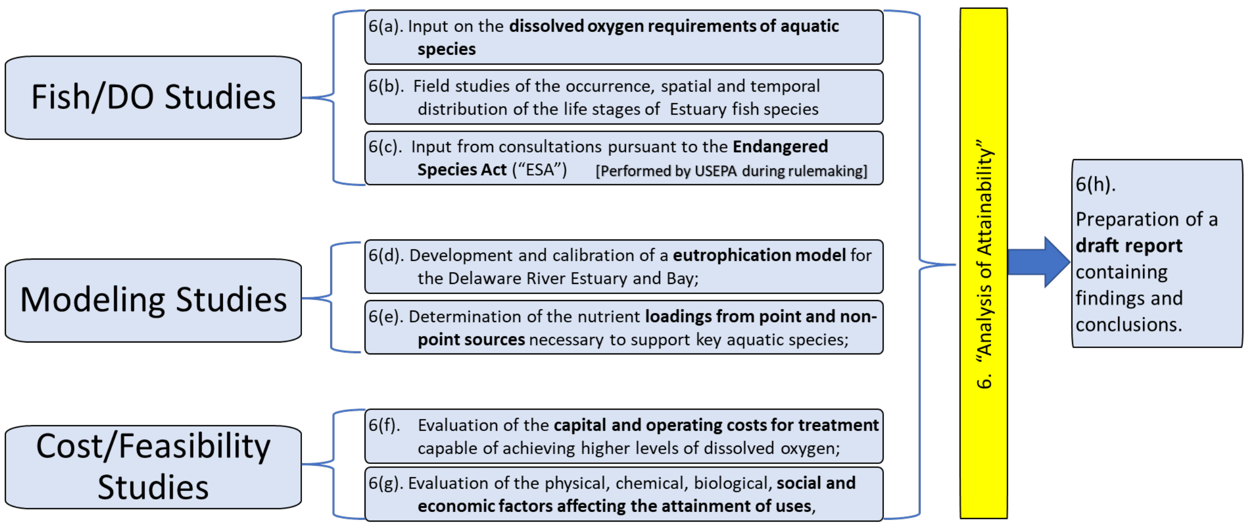


Figure 1-4: Studies required by DRBC Resolution No. 2017-4

defensible and suitable for its intended use, and fully endorsed the staff's scenario results and technical methods utilized for this study.

During public meetings from 2010–2022, the Commission adopted the numbered resolutions (subject to public hearing) and resolutions for the Minutes (not requiring public hearing) listed in chronological order:

- Resolution No. 2010-5: Nutrient monitoring of point-source discharges to the Estuary and Bay
- Resolution No. 2012-7: Formation of Model Expert Panel
- Resolutions Nos. 2013-6 and 2017-5: Analysis of primary productivity by University of Maryland
- Resolution No. 2014-9: Study of effects of low DO and the presence of polychlorinated biphenyls (PCBs) on the early life stages of the Atlantic Sturgeon
- Resolution for the Minutes of March 15, 2017: Consultation services from LimnoTech
- Resolution No. 2017-4: Studies to be undertaken in consultation with co-regulators and dischargers; DRBC to initiate rulemaking to revise the designated aquatic life uses consistent with the results of the identified studies and objectives and goals of the Clean Water Act
- Resolution for the Minutes of Sept. 13, 2017: Monitoring of effluent from Estuary point-source discharges for two years

- Resolution No. 2018-6: Feasibility and cost evaluation of effluent ammonia reduction from key point-source dischargers by Kleinfelder
- Resolution for the Minutes of June 12, 2019: Consultation services for enhancement of source code for the hydrodynamic model (EFDC) from GHD
- Resolution for the Minutes of Dec. 11, 2019: Analytical services for algal composition from Academy of Natural Sciences, Drexel University
- Resolution for the Minutes of Sept. 10, 2020: Revision of AA study period as defined in Resolution No. 2017-4 due to COVID 19 and budget constraints
- Resolution No. 2021-05: Collection of additional information essential to the evaluation of social and economic factors affecting the attainment of uses in the Delaware River Estuary
- Resolution for the Minutes of March 9, 2022: Agreement for professional services with the Environmental Finance Center at the University of Maryland

The results of work performed pursuant to these resolutions culminated in the draft *Analysis of Attainability: Improving Dissolved Oxygen and Aquatic Life Uses in the Delaware River Estuary*, which the Commission published in September 2022.

1.2.3 Resolution for the Minutes of September 7, 2023

In December 2022, in response to a petition by non-governmental organizations, the EPA Administrator determined[15] that revised water quality standards to protect aquatic life in Zone 3, Zone 4, and the upper portion of Zone 5 of the Delaware Estuary were necessary to satisfy requirements of the Clean Water Act. Following such a determination, EPA is required to develop proposed regulations to comply with Section 303(c)(4) of the Clean Water Act, which provides that “the [EPA] Administrator shall promptly prepare and publish proposed regulations setting forth a revised or new water quality standard . . . in any case where the Administrator determines that a revised or new standard is necessary to meet the requirements of [the Clean Water Act].” In recognition of this development, the Commission by a Resolution for the Minutes of September 7, 2023, suspended its own actions to develop and adopt proposed regulations.

Far from abandoning the project of improving water quality in the Delaware River Estuary, to which the Commission remains steadfastly committed, the Commission redefined its role. Rather than promulgating new standards, it announced that it would “continue to provide [the staff’s] scientific, technical, and engineering assistance to support EPA’s process for revising aquatic life designated uses and corresponding criteria for Water Quality Zones 3 and 4 and the upper portion of Zone 5 to attain and maintain propagation of aquatic life, consistent with the staff’s best professional judgment and expertise.”

[15] Letter from Radhika Fox to Steven Tambini, Shawn M. Garvin, Shawn M. LaTourette, and Ramez Ziadeh (Dec. 1, 2022).

The Commission further committed to continuing its coordination and collaboration with state and federal co-regulators during the EPA's rulemaking process. It also promised to "work[] with the EPA, co-regulator states, and interested stakeholders through [DRBC's WQAC] to develop plans, analyses, and, if appropriate, related regulations for the implementation of new aquatic life uses and criteria in the Delaware River Estuary."

In December 2023, EPA proposed revised water quality standards for the FMA and, at the time of publication of this final report, was expected to adopt final standards by the end of 2024. Consistent with DRBC's redefined role described above, and because the final standards to be promulgated by the EPA are not yet known, the title of this final report has been changed from *Analysis of Attainability: Improving Dissolved Oxygen and Aquatic Life,* the title of the September 2022 draft, to *A Pathway for Continued Restoration: Improving Dissolved Oxygen in the Delaware River Estuary*. Importantly, DRBC does not seek with this study to demonstrate attainability of any particular level of DO. Rather, this report focuses on: the pollutant sources that impact DO within the sag; the scale of improvements that can be expected if feasible treatment upgrades and other pollutant reduction measures are implemented; and the costs and relative socio-economic infrastructure cost burden on a utility service area scale. While attainability is not directly addressed, model uncertainty and inter-year variability are explored to a greater degree (Appendix A) than in the draft report. Importantly, this study and the underlying science continue to support the proposition that improving DO will provide for the protection and propagation of fish and other aquatic life throughout the Estuary.

1.3 Purpose

The purpose of this restoration analysis is to synthesize the studies performed pursuant to Resolution No. 2017-4 and provide an analysis of the degree to which dissolved oxygen may be improved in the FMA. This study is purely technical and scientific in nature and does not propose regulatory measures or approaches. It provides a bridge between the upgrade of water quality standards to support fish propagation and the development of wasteload allocations that may be used to implement the revised standards. Specifically, this restoration analysis:

- identifies the individual pollutant sources that impact DO in the FMA, and conversely, those that have no meaningful effect (such that removing them entirely would produce no significant improvement in DO conditions); and
- based on pollutant loading sensitivity and treatment feasibility, and with the understanding that DO is dynamic in space throughout the Estuary and in time throughout the year, characterizes a restoration scenario that would dramatically improve DO in the FMA and thereby support greater health and abundance of aquatic life in this reach.

Following EPA's adoption of revised water quality standards, the Estuary states will be obligated to implement the new standards by placing appropriate effluent limits in permits as necessary. The limits must be designed to allow the receiving waters to satisfy the revised DO criteria. The development of discharger-specific wasteload allocations for multiple discharges within the Delaware River Estuary, a complex tidally influenced waterbody, is expected to be the subject of a future study to be conducted by the DRBC together with the Estuary co-regulator states of Delaware, New Jersey, and Pennsylvania. By identifying the sources and factors that have the potential to influence DO in the Estuary (as well as those that do not), characterizing the scale of improvement that can be expected, and assessing the costs and affordability of implementation, this *Pathway* analysis provides a useful precursor to regulation and an important step towards attainment of the revised standards.

Like the draft *Analysis of Attainability* it replaces, the final *Pathway for Continued Restoration* analysis is supported by the development, calibration, and technically appropriate use of an Estuary eutrophication model. The costs and socioeconomic impacts of the pollutant reduction recommendations are evaluated in supporting studies. Section 2 of this report documents the methodology and process for determining feasible management scenarios to achieve improved water quality within the FMA as characterized by the restoration scenario.

2. Restoration Analysis Methodology

2.1 Water Quality Model

In support of the evaluation of a pathway for restored DO[16] conditions, the DRBC developed a three-dimensional dynamic model of eutrophication processes[17] throughout the Delaware River Estuary from the head of tide at Trenton, New Jersey, to the Atlantic Ocean (Zheng et al., 2024). This effort entailed: 1) engagement of a Model Expert Panel to guide development, calibration, and use of the eutrophication model; 2) a two-year monitoring program to obtain data on nutrient loadings from tributaries and, in cooperation with wastewater utilities, from point sources; 3) field studies on primary productivity and DO gradients; and 4) development and calibration of the eutrophication model, comprised of linked hydrodynamic and water quality models. The eutrophication model was designed to estimate ambient DO levels that can be expected for various pollutant reduction scenarios using a dynamic (time-varying), long-term simulation of diurnal DO patterns.

Modeling eutrophication in the Delaware River Estuary requires an understanding of complex interactions among many processes, including tidal dynamics and water circulation; temperature, salinity, and algal dynamics; nutrient cycling and transformation; and solute exchange across the air/water and sediment/water interfaces. To adequately capture these dynamics, the DRBC developed and linked a three-dimensional (3D) hydrodynamic model of the system, using Environmental Fluid Dynamics Code (EFDC), with a water quality model, using Water Quality Analysis Simulation Program (WASP). The linked hydrodynamic and water quality models utilize the same numerical grid domain, which extends from the mouth of the Delaware Bay (RM 0) to just upstream of the head of tide at Trenton, New Jersey (RM 135). The numerical grid consists of 1,876 horizontal grid cells, 10 vertical layers in the navigation channel, and 11,490 water cells in total. Detailed calibration results are documented in the hydrodynamic (Chen et al., 2024) and water quality (Zheng et al., 2024) model reports. In addition to the full 3D eutrophication model, a two-dimensional (2D) version with only one vertical layer was also developed and utilized for testing and sensitivity purposes. The 2D model takes about 4 hours to complete a one-year simulation, whereas the 3D model takes about 35 hours. The eutrophication model has significantly enhanced the DRBC's and the basin community's understanding of the impact of carbon, nitrogen, and phosphorus loads on DO

[16] DO conditions throughout this report are measured and assessed in terms of water column concentration (mg/L). DO as a percent of saturation level, which is affected by water temperature and salinity, is certainly relevant for fish, which extract DO from the water column through their gills. The eutrophication model of course accounts for all these variables, but concentration is used to assess and compare DO conditions for various scenarios throughout this report.

[17] In this context "eutrophication processes" refers to the physical, chemical, and biological processes that impact (and are impacted by) nutrients and dissolved oxygen, including those driven by algal growth, respiration, photosynthesis, and death. A "eutrophication model" is one that simulates or otherwise accounts for eutrophication processes.

conditions in the Delaware River Estuary, as well as reaeration, sediment oxygen demand, and phytoplankton photosynthesis and respiration.

The primary purpose of the eutrophication modeling study was to develop a modeling tool appropriate for conducting forecast simulations of future pollutant reductions to estimate the resulting ambient DO conditions in the Estuary, and particularly in the FMA. The model was specifically calibrated by DRBC, and endorsed by the Model Expert Panel, for this intended use. Like any model, water quality estimates from this eutrophication model contain some uncertainty and do not exactly reproduce observed calibration data at every location at all times (see detailed discussion in Zheng et al., 2024 as well as the discussion in Section 2.6 of this report). However, by providing a quantitative means of comparing management options for improving DO, the eutrophication model provides a powerful scientific and engineering basis for the DRBC to evaluate possible pathways for DO restoration in the FMA.

2.2 Elements of the Restoration Analysis

Figure 2-1 shows the basic elements of the process employed by the DRBC in accordance with Resolution No. 2017-4. As discussed in Section 2.1, the Commission's analysis was conducted using a complex eutrophication model to dynamically compute the DO levels that would result from candidate test scenarios.

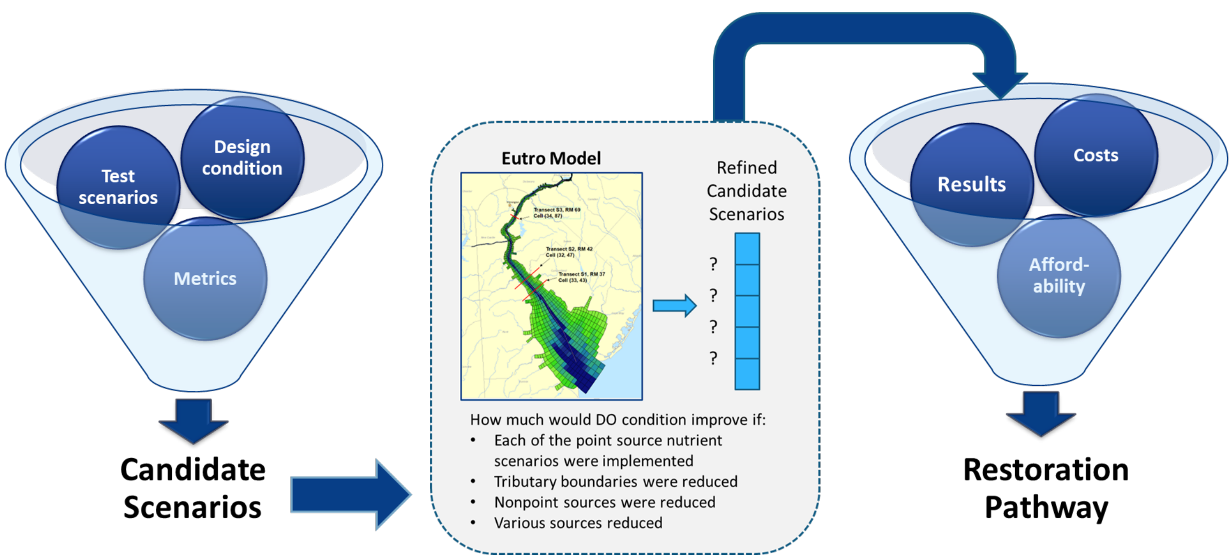


Figure 2-1: Elements of restoration analysis

To select candidate scenarios, a design condition, test scenarios, and metrics must be defined. The design condition (Section 2.3), which simulates the impact of wastewater facilities discharging their permitted flows at their current treatment levels and under critical environmental conditions, provides a baseline from which to develop other test scenarios and against which to compare these scenarios using specific metrics. Test scenarios fall into two general types: pollutant source sensitivity scenarios and pollutant load reduction scenarios. Source sensitivity scenarios are not meant to be realistic or feasible, but instead are designed to assess the relative impacts of pollutant source categories such as wastewater discharges, tributaries, and combined sewer overflows (CSOs). Pollutant load reduction scenarios (Section 2.5), on the other hand, capture the impact of specific management actions, such as the application of advanced treatment to wastewater discharges. Metrics (Section 0) provide the analytical basis for comparing results from one scenario with another. Since DO varies over time and space throughout the Estuary, specific metrics are also needed to characterize a DO restoration scenario.

To prepare recommendations, test scenarios were characterized in terms of feasible DO improvement. Costs were evaluated and considered by estimating the capital and operating costs for individual facilities and combining them to provide an estimate of the total cost under each management scenario. Affordability (Section 4.4) was also evaluated to consider the potential burden of the DO improvement on customers in each service area that would be impacted by additional utility costs. For example, for the Philadelphia Water Department (PWD), the costs were determined for additional treatment at three wastewater treatment plants and used to compute the affordability burden on ratepayers within the PWD service area.

2.3 Design Condition

The design condition is a baseline model simulation against which to compare a range of future condition test scenarios. It represents ambient water quality with wastewater facilities discharging their permitted flows at their current treatment levels and under critical environmental conditions. “Critical” in this context means a combination of temperature, hydrology, and other environmental factors that produce a particularly low DO condition that is a “conservative” condition for design purposes. 2D and 3D model versions of the baseline design condition were constructed, incorporating the following components, each discussed in more detail within this section:

- Hydrologic conditions from 2012, including: (1) tributary and watershed inflows and concentrations, (2) tidal inputs at the mouth of the Bay and the Chesapeake & Delaware (C&D) Canal, and (3) weather inputs.
- Maximum permitted flow rates for all point source discharges. Since actual flows and pollutant loads discharged from wastewater treatment plants were lower on average, the design condition simulation depicts a worse DO condition than actually occurred in 2012.
- Seasonal median effluent concentrations for wastewater discharges, calculated using model-interpolated concentrations assigned based on intensive data collection during the 2018–2019 calibration period.
- River channel bathymetry based upon the deepening of the navigation channel completed in 2016. Numerical tests demonstrate that the deepened navigation channel has insignificant effects on DO concentrations in the Delaware Estuary; nevertheless, post-2016 bathymetry was implemented in both 2D and 3D models.

2.3.1 Hydrologic Conditions

Figure 2-2 and Figure 2-3 present box and whisker plots of DO concentrations at Penn's Landing, Pennsylvania, (USGS 01467200, formerly known as the "Ben Franklin Bridge" station) and Chester, Pennsylvania (USGS 01477050), from 2010–2022 during July and August, when DO in the Delaware River Estuary usually reaches its annual minimum. During 2010–2022, the lowest DO in the Estuary occurred during 2012.

Figure 2-4 and Figure 2-5 depict flow rates for the Delaware River at Trenton, New Jersey (USGS 01463500), and the Schuylkill River at Philadelphia, Pennsylvania (USGS 01474500), during July and August from 2010–2021. The flow rates during summer 2012 were approximately 3,000 and 800 cubic feet per second (cfs), respectively, and are the second- and third-lowest summer flow rates at each station. A minimum flow objective of 3,000 cfs at Trenton was established and codified in the Delaware River Basin Water Code (DRBC, 2013b) to maintain freshwater inflow into the Estuary under normal conditions. Low flows in summer 2012 coincided with low precipitation (Figure 2-6), as 2012 was the third driest summer during the past decade. Monthly total July precipitation from 2010–2021 was lowest in 2012 (Figure 2-7).

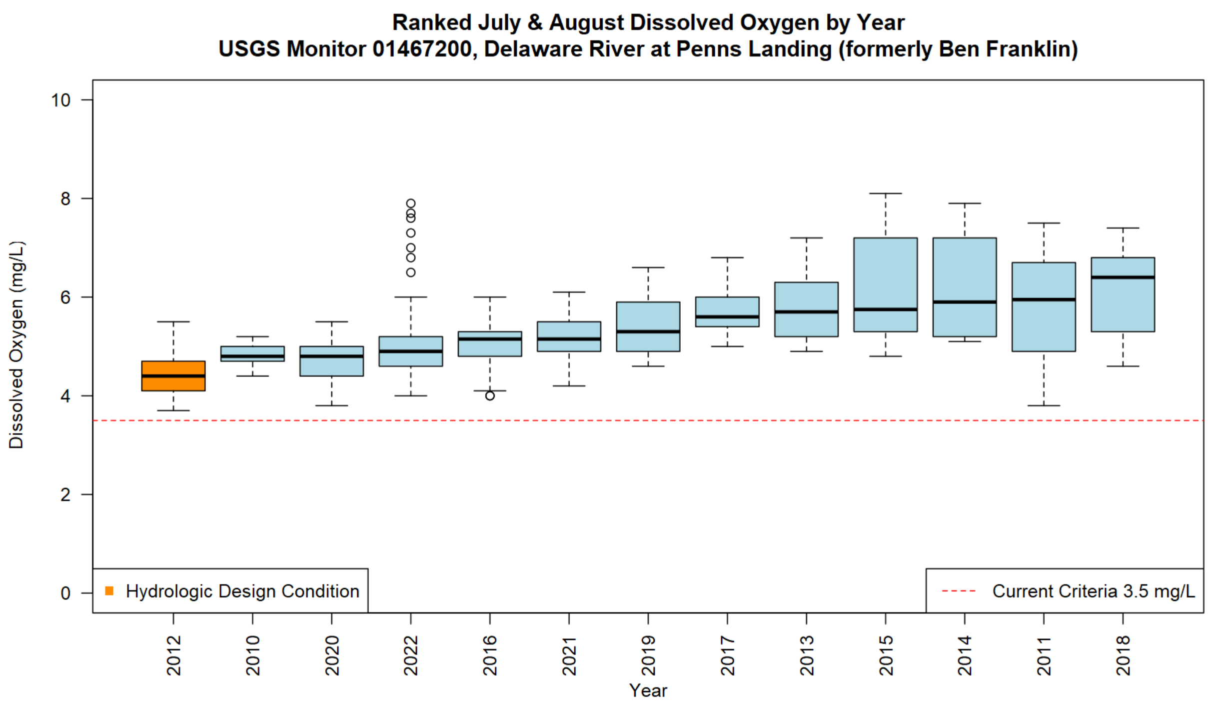


Figure 2-2: Dissolved oxygen at Penn's Landing during July and August from 2010–2022

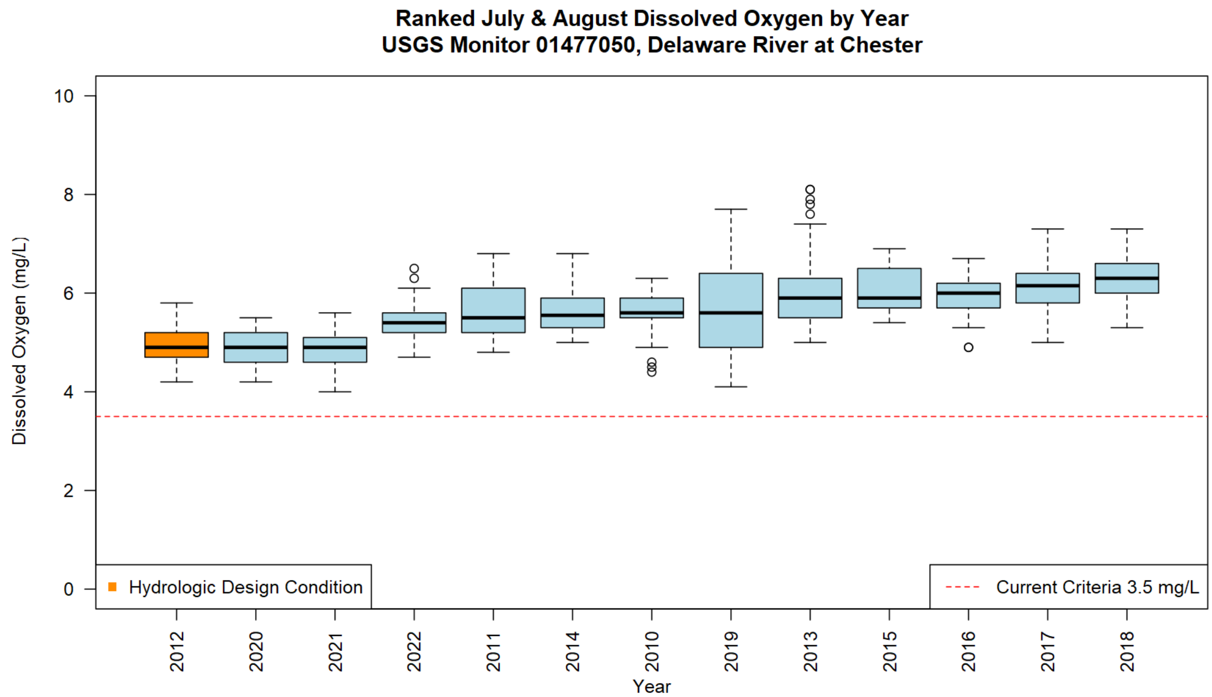


Figure 2-3: Dissolved oxygen at Chester during July and August from 2010–2022

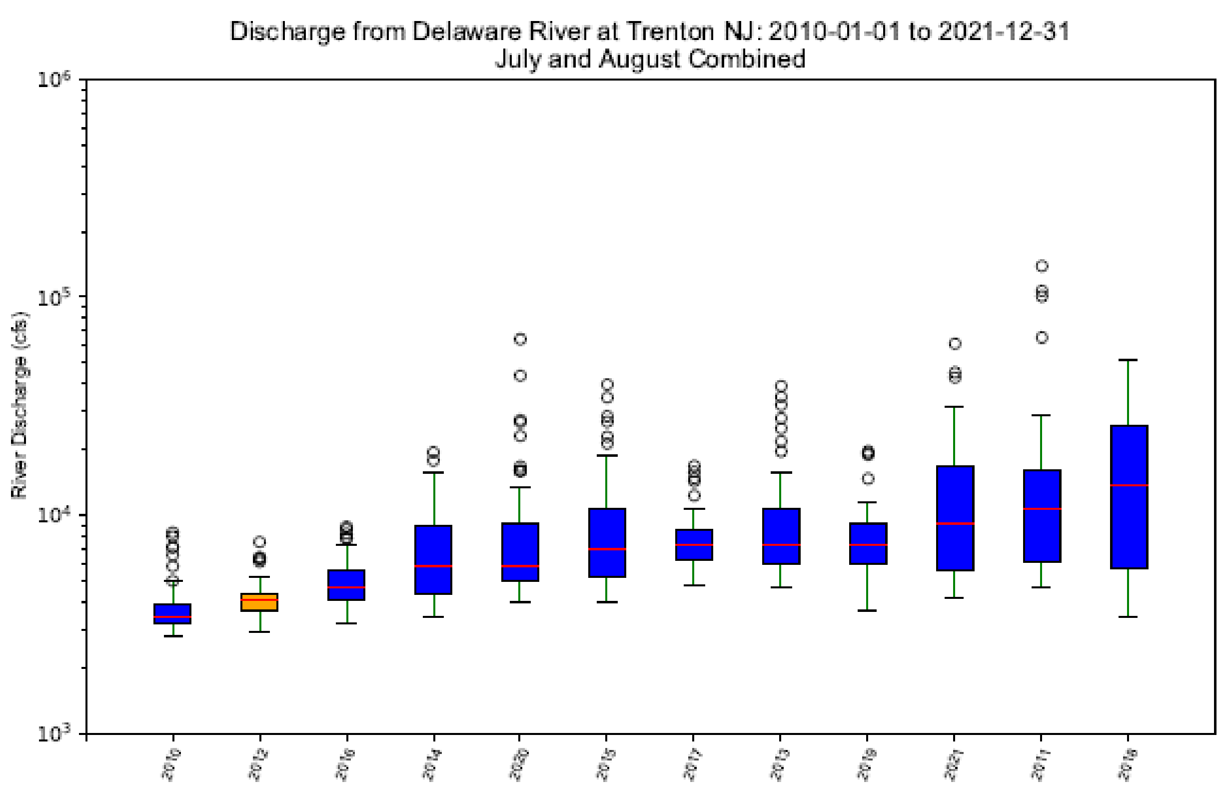


Figure 2-4: Daily flow of the Delaware River at Trenton during July and August from 2010–2021

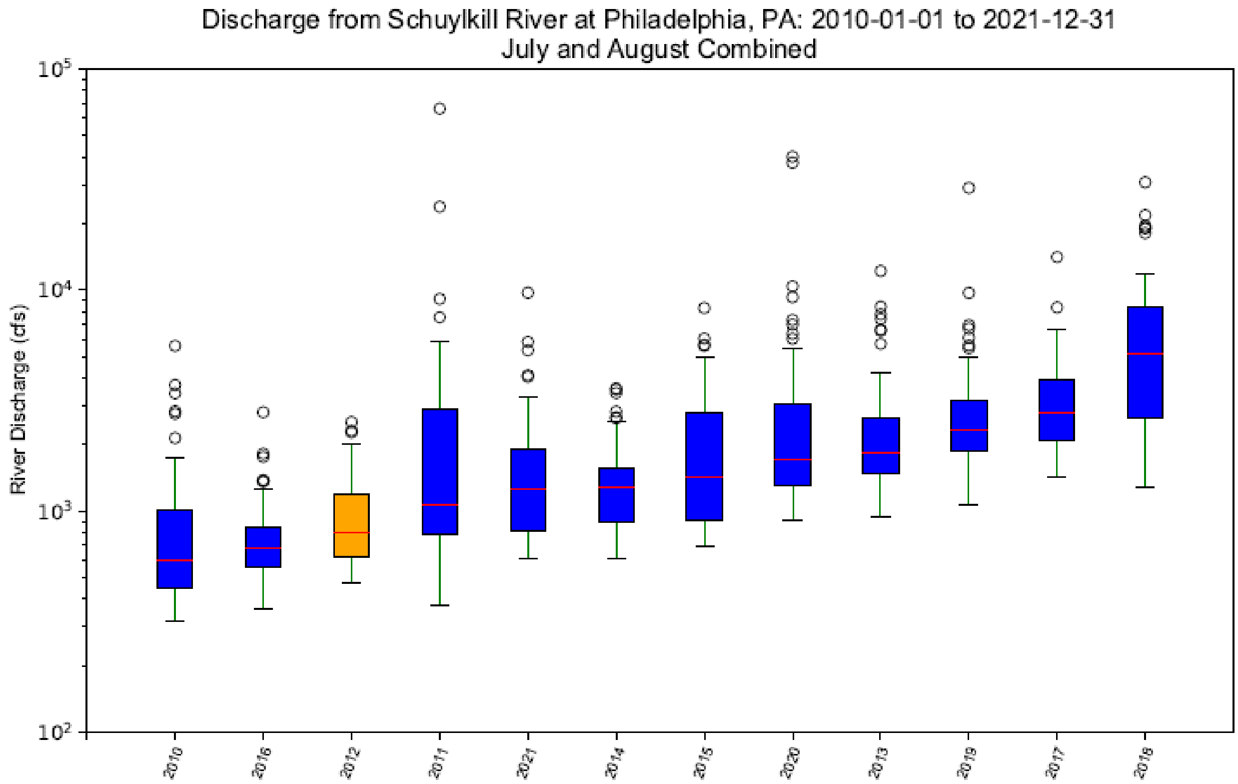


Figure 2-5: Daily flow of the Schuylkill River at Philadelphia during July and August from 2010–2021

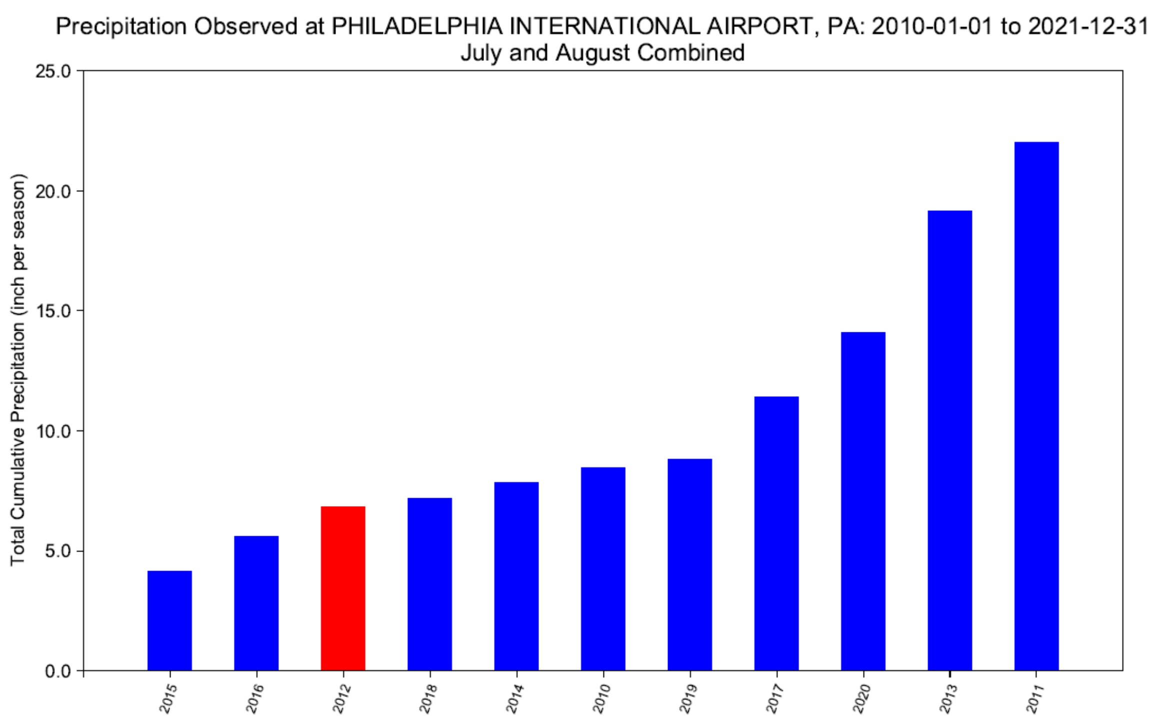
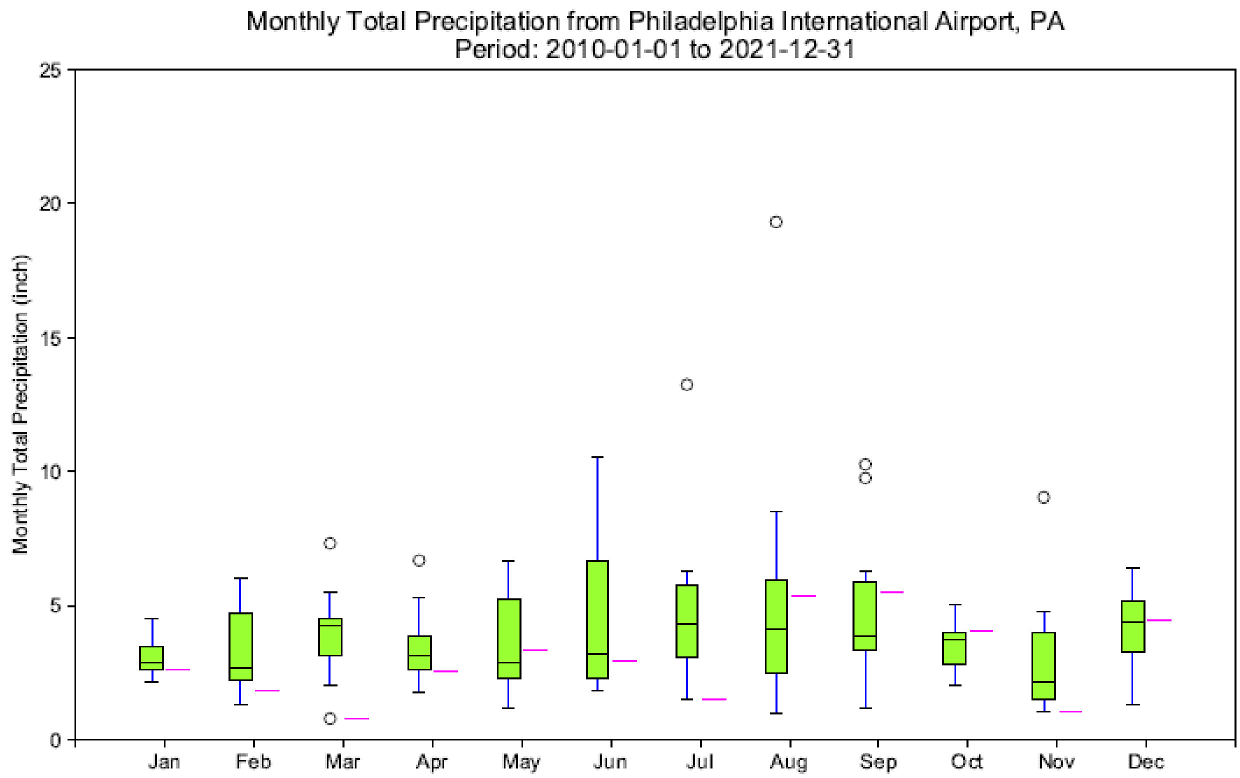


Figure 2-6: Precipitation at Philadelphia International Airport during July and August from 2010–2021



Monthly precipitation in 2012 (pink lines) is shown for comparison with the distribution of monthly precipitation values from 2010 to 2021 (green boxes and whiskers).

Figure 2-7: Historical monthly total precipitation statistics at Philadelphia for 2010–2021

The dry weather and low flows from tributaries in 2012 resulted in lower DO in the Estuary, likely due to less dilution by ambient waters and longer residence times for the consumption of oxidizable organic material than during other years over the last decade. This provides the justification for selecting the 2012 hydrologic condition as a conservative baseline for assessing DO improvement.

2.3.2 Wastewater Characteristics

Typically, wastewater treatment plants discharge well below their permitted flow rates under normal operating conditions (i.e., except for heavy storm events); however, wastewater plants may lawfully discharge at the permitted flow level at any time. The permitted flow rates[18] established by individual National Pollutant Discharge Elimination System (NPDES) permits were used to characterize wastewater

[18] During 2022, DRBC became aware that DELCORA sought to increase the permitted flow of its plant to 70 million gallons per day (MGD). Although the currently (as of August 2024) permitted flow for DELCORA is 44 MGD, the analyses performed in this study were based on the 70-MGD permitted flow anticipated in 2022.

discharges in the design condition. Effluent concentrations of simulated constituents[19] were set to "summer" (May–October) and "winter" (November–April) median values calculated based on model-interpolated concentrations assigned based on intensive data collection during the 2018–2019 calibration period (Zheng et al., 2024). Permitted flows and key effluent concentrations for the baseline scenario for discharges identified as potential candidates for load reduction are summarized in Table 2-1 (summer) and Table 2-2 (winter). Figure 2-8 and Figure 2-9 present the load distributions of ammonia nitrogen and CBOD, respectively, summarized by flow type for Zones 2–5 in the design condition.

[19] Relevant model constituents include: three forms of carbon (ultimate CBOD, refractory CBOD, and detrital carbon); four forms of nitrogen (ammonia, nitrate, dissolved organic nitrogen, and detrital nitrogen); three forms of phosphorus (inorganic phosphorus, dissolved organic phosphorus, and detrital phosphorus); and dissolved oxygen.

Table 2-1: Baseline permitted flows and key pollutant effluent concentrations, May–October

Discharge Name	NPDES # Outfall #	Flow (MGD)	NH34 (mg-N/L)	Phosphate (mg-P/L)	CBODU (mg-O2/L)	DO (mg-O2/L)
PWD Northeast Water Pollution Control Plant	PA0026689-001	210	4.4	0.1	9.6	5.4
Camden County Municipal Utilities Authority	NJ0026182-001A	80	17.3	1.4	8.6	5.1
PWD Southeast Water Pollution Control Plant	PA0026662-001	112	8.6	0.1	9.4	4.9
PWD Southwest Water Pollution Control Plant	PA0026671-001	200	19.0	0.1	10.5	5.1
Gloucester County Utilities Authority	NJ0024686-001A	27	23.9	2.2	11.9	7.6
DELCORA	PA0027103-001	70	3.8	1.4	14.7	6.7
City of Wilmington Wastewater Treatment Plant	DE0020320-001	134	9.5	0.6	10.9	5.5
Hamilton Twp Water Pollution Control Facility	NJ0026301-001A	16	27.0	3.5	25.7	7.2
Lower Bucks County Joint Municipal Authority	PA0026468-001	10	19.7	1.7	12.2	3.7
Morrisville Borough Municipal Authority	PA0026701-201	7.1	9.7	2.3	10.4	7.6
Trenton Sewer Utility	NJ0020923-001A	20	5.4	1.9	12.3	8.5
Willingboro Water Pollution Control Plant	NJ0023361-001A	5.22	1.4	0.8	18.2	7.4
Cinnaminson Sewerage Authority	NJ0024007-001A	2	16.0	2.4	9.6	0.5
City of Millville Sewage Treatment Authority	NJ0029467-001A	5	26.2	2.0	11.2	7.4
Cumberland County Utilities Authority	NJ0024651-001A	7	4.7	0.5	10.3	7.4
Logan Township Municipal Utilities Authority	NJ0027545-001A	2.75	6.4	1.6	9.9	6.9
Florence Township Sewage Treatment Plant	NJ0023701-001A	2.5	5.9	1.2	27.9	7.9
Penns Grove Sewerage Authority	NJ0024023-001A	0.75	19.5	0.6	13.8	8.4
Beverly Sewerage Authority	NJ0027481-001	1	14.5	4.0	16.0	4.0

Table 2-2: Baseline permitted flows and key pollutant effluent concentrations, November–April

Discharge Name	NPDES # Outfall #	Flow (MGD)	NH34 (mg-N/L)	Phosphate (mg-P/L)	CBODU (mg-O2/L)	DO (mg-O2/L)
PWD Northeast Water Pollution Control Plant	PA0026689-001	210	5.6	0.1	10.8	5.8
Camden County Municipal Utilities Authority	NJ0026182-001A	80	15.6	0.8	10.7	5.9
PWD Southeast Water Pollution Control Plant	PA0026662-001	112	8.0	0.1	10.6	5.9
PWD Southwest Water Pollution Control Plant	PA0026671-001	200	19.0	0.1	12.8	6.8
Gloucester County Utilities Authority	NJ0024686-001A	27	20.7	1.8	13.7	7.5
DELCORA	PA0027103-001	70	9.1	0.8	17.3	7.5
City of Wilmington Wastewater Treatment Plant	DE0020320-001	134	13.2	0.4	13.1	5.6
Hamilton Twp Water Pollution Control Facility	NJ0026301-001A	16	25.2	2.7	26.0	7.9
Lower Bucks County Joint Municipal Authority	PA0026468-001	10	20.6	1.7	14.7	4.0
Morrisville Borough Municipal Authority	PA0026701-201	7.1	9.1	1.4	14.2	9.8
Trenton Sewer Utility	NJ0020923-001A	20	6.4	1.3	10.6	8.5
Willingboro Water Pollution Control Plant	NJ0023361-001A	5.22	3.3	0.9	19.6	9.0
Cinnaminson Sewerage Authority	NJ0024007-001A	2	18.2	1.8	12.3	0.5
City of Millville Sewage Treatment Authority	NJ0029467-001A	5	28.5	1.5	15.6	7.9
Cumberland County Utilities Authority	NJ0024651-001A	7	9.2	1.2	13.1	7.6
Logan Township Municipal Utilities Authority	NJ0027545-001A	2.75	6.4	1.6	9.9	6.9
Florence Township Sewage Treatment Plant	NJ0023701-001A	2.5	3.1	1.3	25.3	8.9
Penns Grove Sewerage Authority	NJ0024023-001A	0.75	19.5	0.6	13.8	8.4
Beverly Sewerage Authority	NJ0027481-001	1	14.5	4.0	16.0	4.0

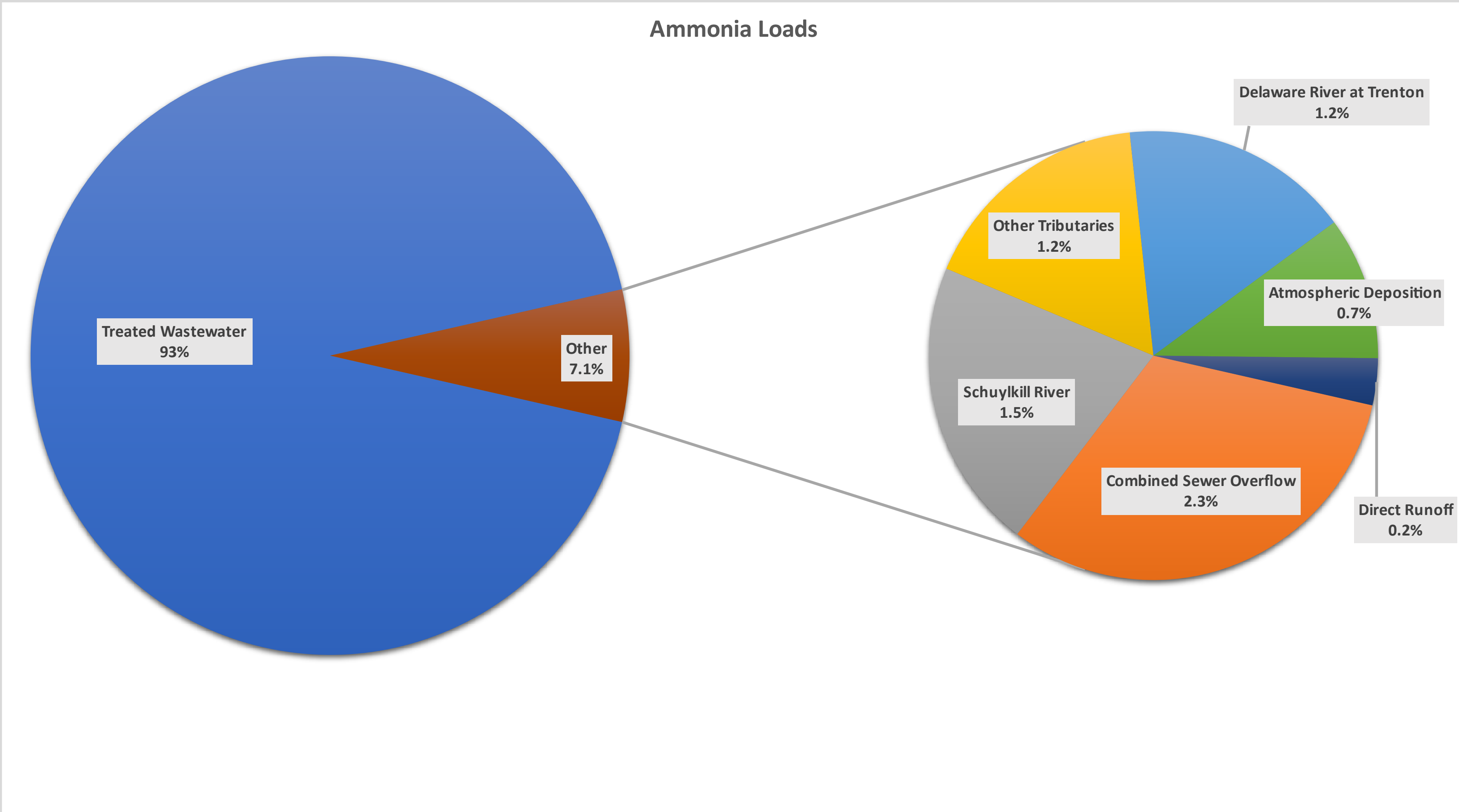


Figure 2-8: Ammonia loading composition in design condition

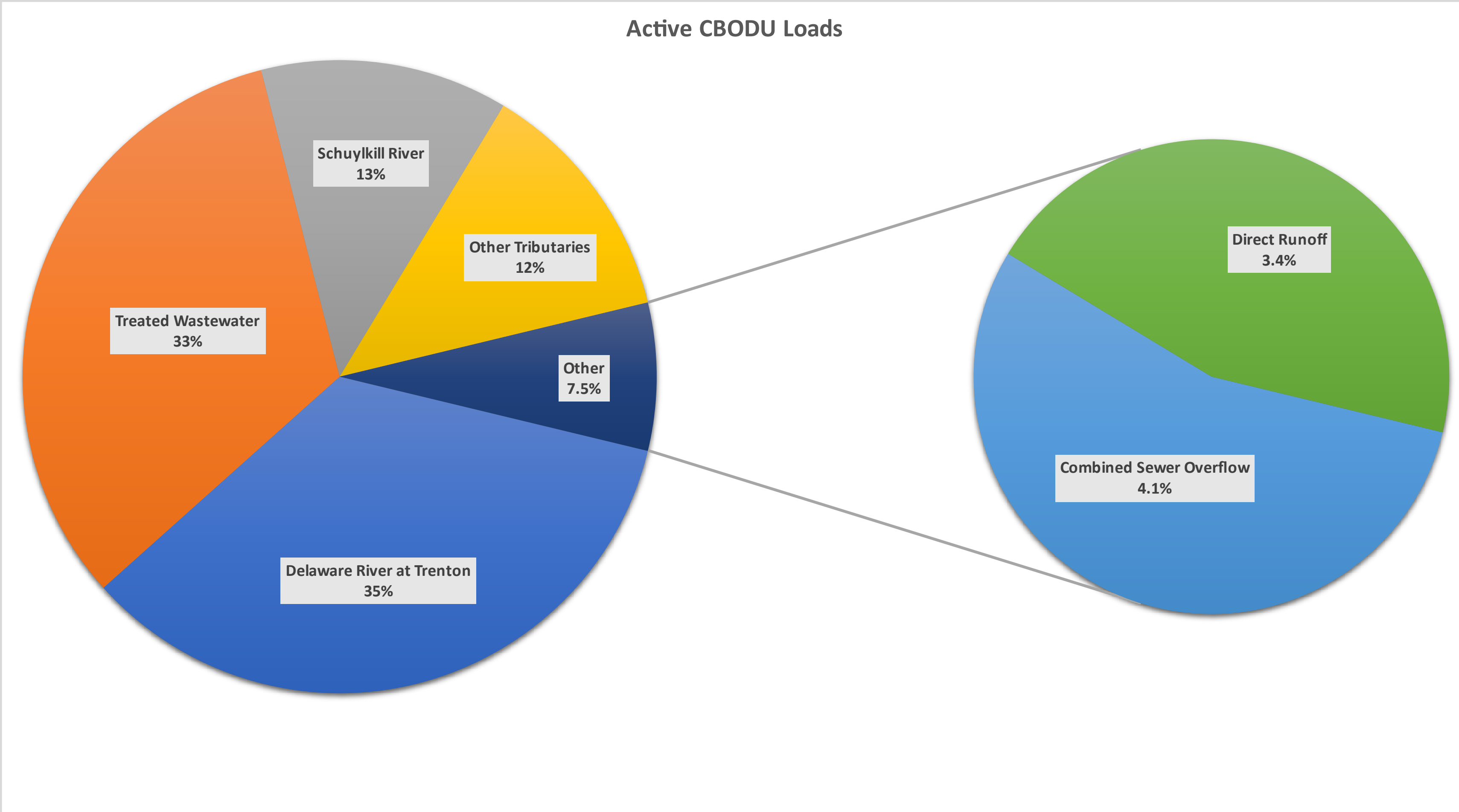


Figure 2-9: Active CBODU loading composition in design condition

2.3.3 Sensitivity of DO to Effluent Flow Rates

A series of modeling tests were conducted to address uncertainty in results due to differences between the permitted wastewater flow rates used in the design condition and "actual" wastewater discharge flow rates, which are generally lower than the permitted rate. First, two 3D simulations were performed using the same effluent pollutant loads but different flow rates for wastewater plants. One was assigned permitted flow rates (as in the design condition) and the other actual flow rates from 2012. Two different sets of constant concentrations were assigned to each simulation, such that, accounting for their different flows, the total annual loads were identical. The goal for this test was to confirm that the hydrodynamic differences between actual (variable and generally lower) and permitted (constant and generally higher) effluent flows were not causing a difference in DO independent of the nutrient loads delivered. The 1st percentile results (see Section 2.4.1 for a description of how this metric is calculated and displayed) are almost identical between the two simulations (Figure 2-10), indicating that the hydrodynamic conditions caused by differences in effluent flows are not consequential to ambient DO in the Estuary.

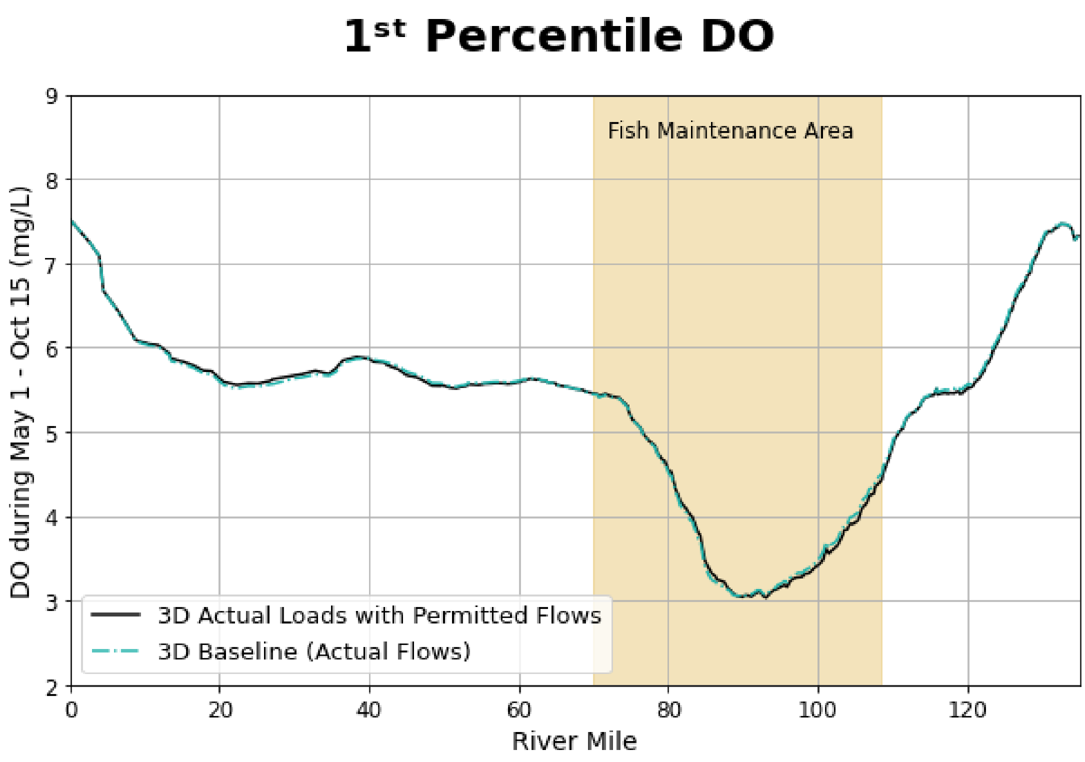


Figure 2-10: Comparison between scenarios with same wastewater load but different flows

Second, comparisons between the 2D baseline scenario and a scenario with effluent ammonia from select discharges reduced to 1.5 mg/L were prepared (Figure 2-11) using: (1) permitted wastewater flow rates (upper panel) from 2012; and (2) actual wastewater flow rates from 2012 (lower panel). For this test, the twelve (12) Tier 1 wastewater treatment plants were selected. Tier 1 discharges were identified based on two years of effluent loading data collected during the 2010s; the Tier 1 discharges together constitute 95% of the total point source nutrient load.[20]

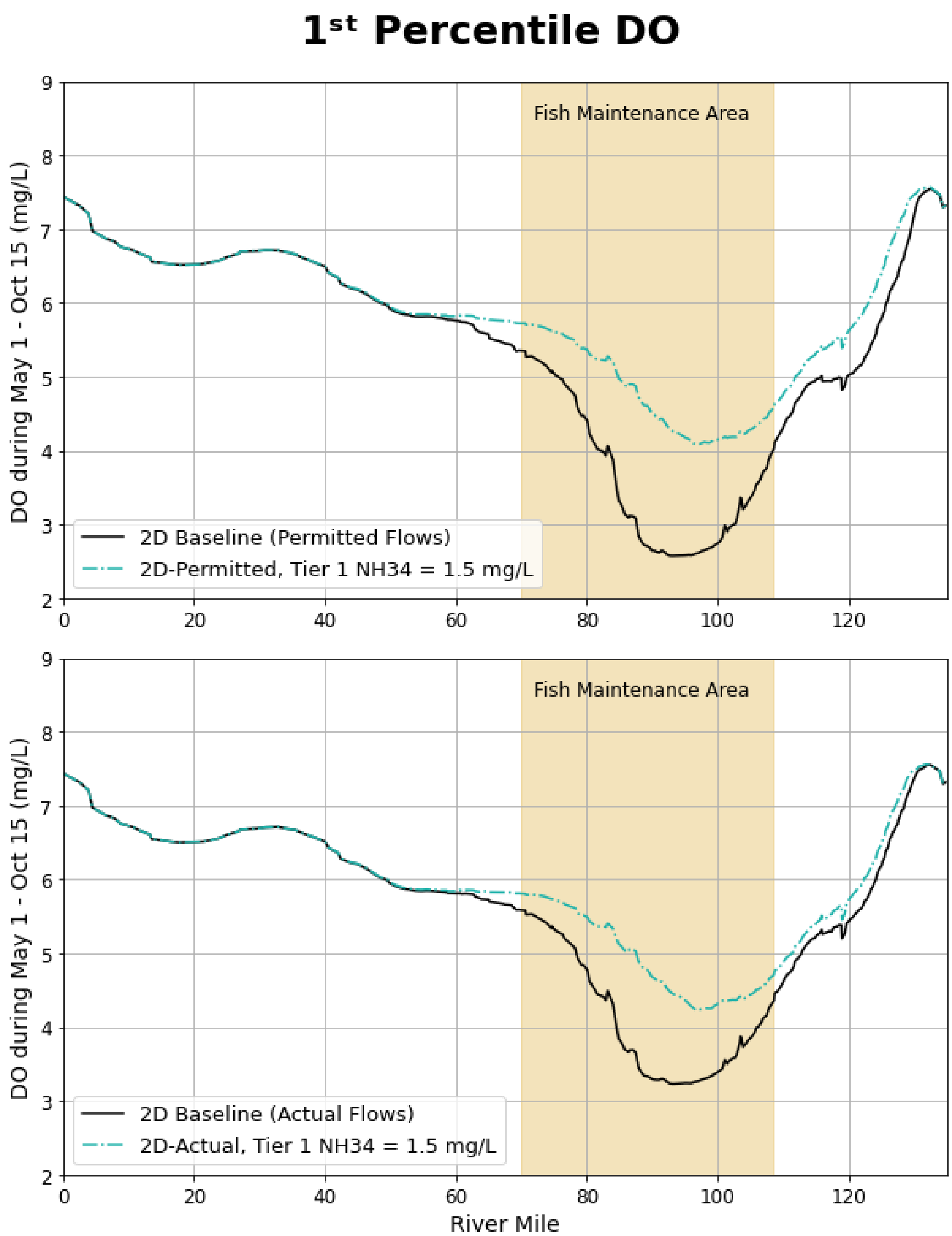


Figure 2-11: 2D scenario comparisons using permitted and actual wastewater flows

[20] Specifically, Tier 1 dischargers were identified as those that constitute: a) 95% of ammonia, total Kjeldahl nitrogen, or 5-day biochemical oxygen demand loads; AND b) 95% of total phosphorus, soluble reactive phosphorus, nitrate, or total nitrogen loads. See presentation by John Yagecic during Water Quality Advisory Meeting on August 24, 2017. https://www.nj.gov/drbc/library/documents/WQAC/082417/yagecic_point-source-monitoring.pdf

In Figure 2-11, the predicted low (1st percentile) DO concentrations from the permitted-flows baseline are lower than those from the actual-flows baseline; this was expected, since the permitted-flow baseline, with higher flows and equal concentrations, results in a higher ammonia load to the Estuary. However, the predicted low DO concentrations for the reduced-ammonia scenarios were more similar between permitted and actual flows, especially within the FMA. This result suggests that the conservative use of permitted effluent flows, which accounts for anticipated increases in effluent discharge rates over time, is less significant for load reduction scenarios compared to the baseline scenario.

2.4 Metrics to Compare Scenarios

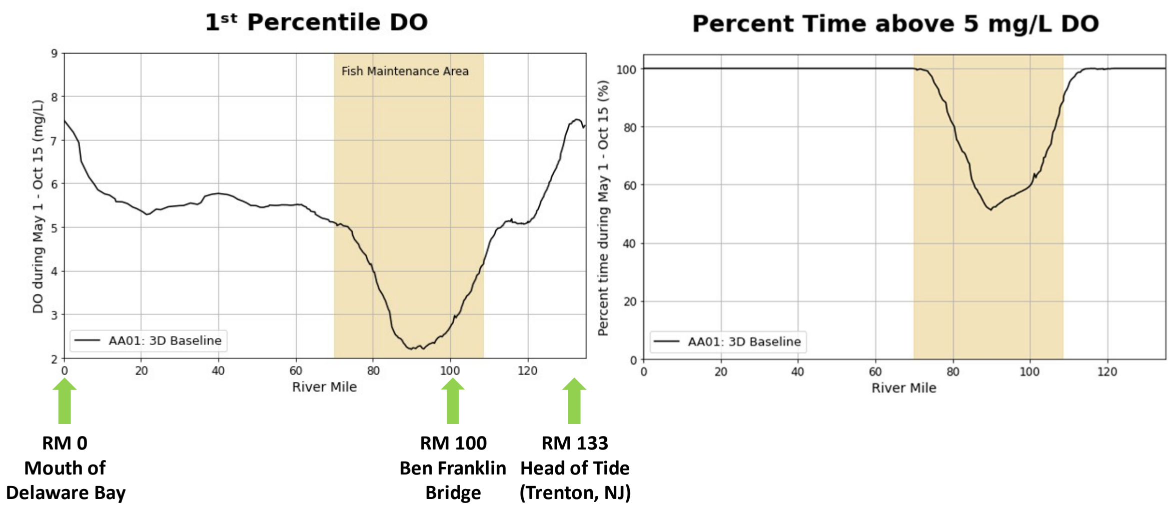
Several metrics were developed to compare modeled DO output under different scenarios. Because model output comprises 2-hour DO time series within each model cell (thousands of locations), this output needed to be processed before scenarios could be compared effectively. Each metric described below is designed to characterize the distribution, magnitude, frequency, and/or duration of low-DO values throughout the Estuary. Each metric was evaluated for the period from May 1 to October 15, the "critical propagation season." This "summer" season reflects the temporal overlap between historically low DO events and important stages in larval and juvenile development in which fish may be particularly vulnerable to low DO concentrations.

2.4.1 Longitudinal Plots: DO Percentiles and "Percent-Above"

The longitudinal plots depict modeled changes in water quality from just upstream of the head of tide at Trenton, New Jersey, (RM 135) on the right-hand side of the plot to where the Delaware Bay meets the Atlantic Ocean (RM 0) on the left (Figure 2-12). Each value plotted represents a cross-section of the model in space (all cells at the same transect, or along-channel, coordinate) over a period of time (the critical propagation season). Two metrics are presented using longitudinal plots.

- **DO percentiles.** A percentile DO value represents the distribution of DO concentration results during the critical propagation season. The 1st percentile DO is the value for which 1% of modeled DO values are lower and 99% are higher. In this study, the 1st, 10th, 25th and 50th percentile values are presented to characterize the lower end of predicted DO distributions for each scenario and the 1st percentile DO generally characterizes the minimum DO at a particular transect.
- **Percent time above.** The duration of low-DO events during the critical propagation season was evaluated using the percent of time that modeled DO concentration is above 4, 5, 6 and 7 mg/L during the critical propagation season.

In the main body of this report, results for 1st percentile DO and percent time above 5 mg/L are shown for illustrative purposes. Similar trends were observed using the other percentiles (i.e., the 10th,25th, and 50th percentiles) and DO thresholds (i.e., percent time above 4, 6, and 7 mg/L); those results can be viewed in Appendices B and C.



1st percentile DO (left) and percent time above 5 mg/L (right) plotted against River Mile for the 3D baseline scenario (see Section 2.3). The Fish Maintenance Area is shaded in yellow.

Figure 2-12: Example longitudinal plots for the 3D baseline scenario

2.4.2 DO Relative Stress Index

The DO Relative Stress Index (RSI) was developed by the DRBC to compare the potential stress to aquatic life from low DO under different scenarios by capturing the frequency, magnitude, and duration of low-DO events in a single number. This metric is intended only for scenario comparison; it compares, rather than absolutely quantifies, potential stress to aquatic life. The calculation was designed such that lower DO values represent exponentially more "stress" than higher DO values. For example, a DO increase from 3.5 mg/L to 4.0 mg/L would represent a bigger decrease in RSI than a DO increase from 4.0 mg/L to 4.5 mg/L. RSI results were also plotted longitudinally by river mile; however, these plots show only the FMA (RM 70–108.4), as RSI values are typically low outside of the FMA during all scenarios. An example RSI plot is shown in Figure 2-13.

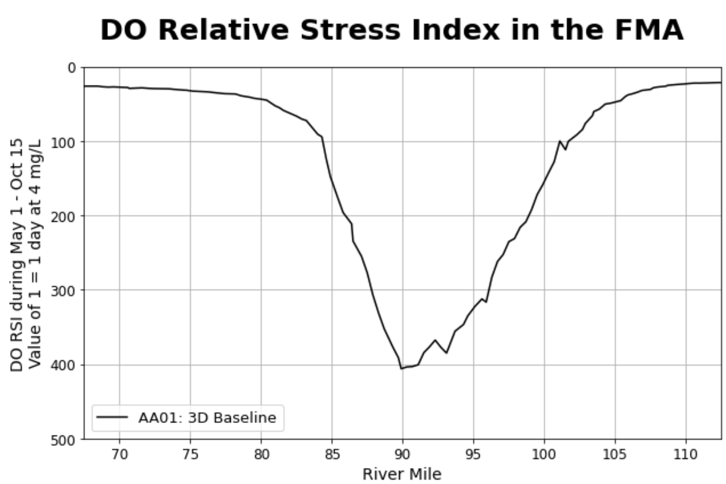
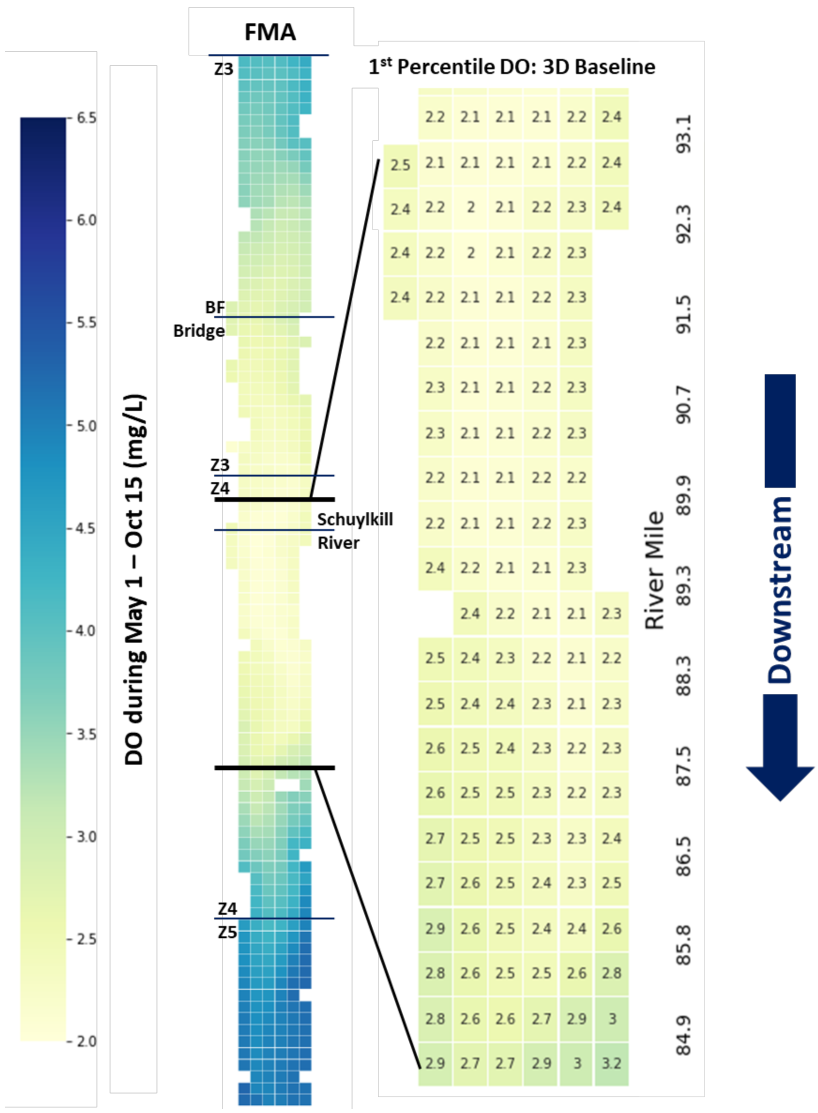


Figure 2-13: Example DO Relative Stress Index plot for the 3D baseline scenario

2.4.3 Tabular Maps

To visualize spatial patterns in DO not apparent in longitudinal plots (e.g., variation within a cross-section), tabular maps were generated. These maps display each model coordinate within the FMA as a square, colored according to the depth-averaged 1st percentile from the DO time-series at that location. Figure 2-14 displays results from the 3D baseline scenario. The map on the left displays the entire FMA, while the map on the right zooms into the DO sag and displays the depth-averaged 1st percentile DO concentration value for each location. Recall that the 1st percentile represents a very infrequent, low DO level (Section 2.4.1).



Left: Each cell location in the FMA colored by 1st percentile DO during May 1–October 15, 3D baseline scenario. Zone boundaries, Ben Franklin Bridge, and the Schuylkill River confluence are labelled. Right: Zoom in to a 10-mile section at the lowest part of the DO sag.

Figure 2-14: Example tabular maps for the 3D baseline scenario

2.5 Pollutant Load Reduction Scenarios

As described above, two types of test scenarios—source sensitivity scenarios and load reduction scenarios—were used to explore the sensitivity of DO in the FMA to various pollutant sources. The load reduction scenarios tested combinations of additional feasible wastewater treatment for nitrogen and the associated reductions in pollutant effluent concentrations.

As part of this analysis under Resolution No. 2017-4, the DRBC commissioned a Nitrogen Reduction Cost Estimation Study (DRBC, 2021). In this study, Kleinfelder developed planning-level cost estimates for four levels of reduced effluent ammonia and total nitrogen concentrations for each of the twelve Tier 1 wastewater treatment plants discharging to the Estuary: ammonia levels of 10, 5.0, and 1.5 mg/L, and a total nitrogen level of 4.0 mg/L. The evaluation results were presented to the WQAC on August 24, 2017.

Kleinfelder identified three broad categories of existing wastewater treatment types among the Tier 1 discharges. These include pure oxygen activated sludge, fixed film, and conventional activated sludge. Kleinfelder further identified proven treatment technologies with long-term records of performance to ensure a reasonable degree of confidence in plant upgrade performance and the ability to appropriately estimate construction and operating costs for achieving the four effluent nitrogen levels for each of the existing treatment types. Specifically, Kleinfelder identified addition of a biological aerated filter (BAF) along with other process modifications for the pure oxygen activated sludge and fixed film plants, and conversion to an integrated fixed film activated sludge (IFAS) process with other process modifications for the conventional activated sludge plants.

According to the Kleinfelder report, for pure oxygen activated sludge plants and fixed film plants to achieve an effluent ammonia concentration of 1.5 mg/L, the entire plant effluent flow must be treated by a fully nitrifying BAF. For those two types of plants, 1.5 mg/L ammonia represents full treatment. Conventional activated sludge effluent ammonia treatment with IFAS may be adjusted to achieve different effluent ammonia targets depending on the quantity of IFAS media added. However, the Kleinfelder report highlights significant treatment bottlenecks and challenges that limit the practical treatment of effluent ammonia for large wastewater treatment plants. As a result, DRBC understands 1.5 mg/L ammonia to be a practical lower treatment limit for wastewater treatment plants.

EPA's guidance for NPDES permit writers (EPA, 2010) recognizes that wastewater influent flow and concentration are highly variable and that effluent concentration will also be variable. As such, although day to day effluent concentrations may be lower or higher than 1.5 mg/L ammonia, 1.5 mg/L ammonia represents an attainable level consistent with EPA guidance.

Load reduction scenarios were prepared by assigning constant effluent concentrations during the "summer" (May 1–October 31) to the discharges being tested. Ammonia was set to the level being tested, while nitrate (NO3) and CBOD were adjusted accordingly, as shown in Table 2-3. When a particular scenario required a reduction in summer ammonia concentration, the difference was added to nitrate to

Table 2-3: Summer effluent CBOD and nitrate adjustments for load reduction scenarios

	Baseline			NH34 ≤ 10 mg/L		NH34 ≤ 5 mg/L		NH34 ≤ 1.5 mg/L		TN ≤ 4 mg/L	
Discharge	NH34	NO3	CBOD	NO3	CBOD	NO3	CBOD	NO3	CBOD	NO3	CBOD
PWD Northeast WPCP	4.4	2.7	9.6	NC	NC	NC	NC	5.6	5.9	1.5	5.6
Camden County MUA	17.3	1.5	8.6	8.8	6.2	13.8	5.5	17.3	5.0	1.5	5.0
PWD Southeast WPCP	8.6	0.3	9.4	NC	NC	3.9	7.4	7.4	6.3	1.5	3.1
PWD Southwest WPCP	19	1.3	10.5	10.3	9.6	15.3	9.4	18.8	9.2	1.5	9.2
Gloucester County UA	23.9	1.8	11.9	15.7	10.2	20.7	8.5	24.2	6.9	1.5	5.0
DELCORA	3.8	6.5	14.7	NC	NC	NC	NC	8.8	9.5	1.5	5.2
City of Wilmington WWTP	9.5	3.4	10.9	NC	NC	7.9	7.2	11.4	5.4	1.5	5.5
Hamilton Twp WPCF	27	4.8	25.7	21.8	10.3	26.8	6.2	30.3	3.3	1.5	3.3
Lower Bucks County Joint MA	19.7	2.4	12.2	12.1	10.0	17.1	7.7	20.6	5.4	1.5	6.8
Trenton Sewer Utility	5.43	7.2	12.3	NC	NC	7.63	6.33	11.13	2.12	1.5	2.12
Morrisville Borough MA	9.7	12.7	10.4	12.4	6.03	17.4	4.04	20.9	2.65	1.5	2.65
Willingboro WPCP	1.4	15.4	18.2	NC	NC	NC	NC	NC	NC	1.5	4.74
Cumberland County UA	4.7	2.8	10.3	NC	NC	NC	NC	6.0	NC*	1.5	NC*
Logan Township	6.43	2.0	9.9	NC	NC	3.43	NC*	6.93	NC*	1.5	NC*
Florence Township	5.9	3.8	27.9	NC	NC	4.7	NC*	8.2	NC*	1.5	NC*
Penns Grove	19.5	0.4	13.8	9.9	NC*	14.9	NC*	18.4	NC*	NC	NC
Beverly	14.5	5.5	16.0	10	NC*	15	NC*	18.5	NC*	1.5	NC*
Cinnaminson	16.0	3.7	9.6	9.7	NC*	14.7	NC*	18.2	NC*	1.5	NC*
City of Millville	26.2	0.16	11.1	16.4	NC*	21.4	NC*	24.9	NC*	NC	NC

NC No change (Baseline values were used).
NC* CBOD values were adjusted for the 12 Tier 1 discharges only.

keep the total nitrogen level constant. This approach assumes that ammonia would be reduced in the wastewater by nitrification, resulting in additional nitrate. Associated CBOD reductions were assumed for Tier 1 discharges based on the cost and feasibility study (DRBC, 2021); essentially, these reductions represent the decrease in ultimate CBOD that would be expected for a particular level of ammonia treatment. Note that for simulating a total nitrogen concentration of 4.0 mg/L, the following composition of nitrogen components was assumed: 1.5 mg/L ammonia, 1.5 mg/L nitrate, 0.75 mg/L organic nitrogen, and 0.25 mg/L detrital nitrogen.

2.6 Water Quality Model Uncertainty and Ongoing Improvement

The eutrophication model applied in this study, like any complex modeling tool, produces results with some degree of uncertainty. There are many sources of uncertainty including: limitations imposed by practical model simplifications such as the scale of computational cells; model equations that imperfectly describe physical, chemical and biological processes; data that reflect measurement uncertainty as well as limitations in locations and frequency of measurements; and of course imperfect knowledge regarding all the factors that impact dissolved oxygen at any particular time and place in a system as large and complex as the Delaware River Estuary. In addition to model uncertainty, this restoration analysis was based on specific scenarios that incorporate a degree of conservatism that is appropriate for the analysis being performed but limit the application of the results. For instance, the design condition described in this report relies on the conservative assumptions that all wastewater treatment plants discharge at their permitted flow volumes and that hydrologic conditions will reflect baseline conditions from a low-DO year (2012).

With input from the Model Expert Panel, work is ongoing to continuously improve the model consistent with agency goals and resources. Ongoing work is specifically focused on two model improvements that, while not critical to the findings of this restoration analysis, may reduce uncertainty in ways that will enhance future application of the model.

- The model applied in this study uses static, externally-defined sediment oxygen demand (SOD) values (Zheng et al., 2024); work is underway to incorporate a sediment diagenesis model that will predict SOD dynamically under different scenarios.
- The model applied in this study combines the phytoplankton communities in the freshwater estuary into one group (Zheng et al., 2024); work is underway to better characterize and simulate the algal communities in the freshwater tidal river.

For a more complete discussion of model limitations and uncertainty, refer to recent reports that document the hydrodynamic model (Chen et al., 2024) and eutrophication model (Zheng et al., 2024) in more detail.

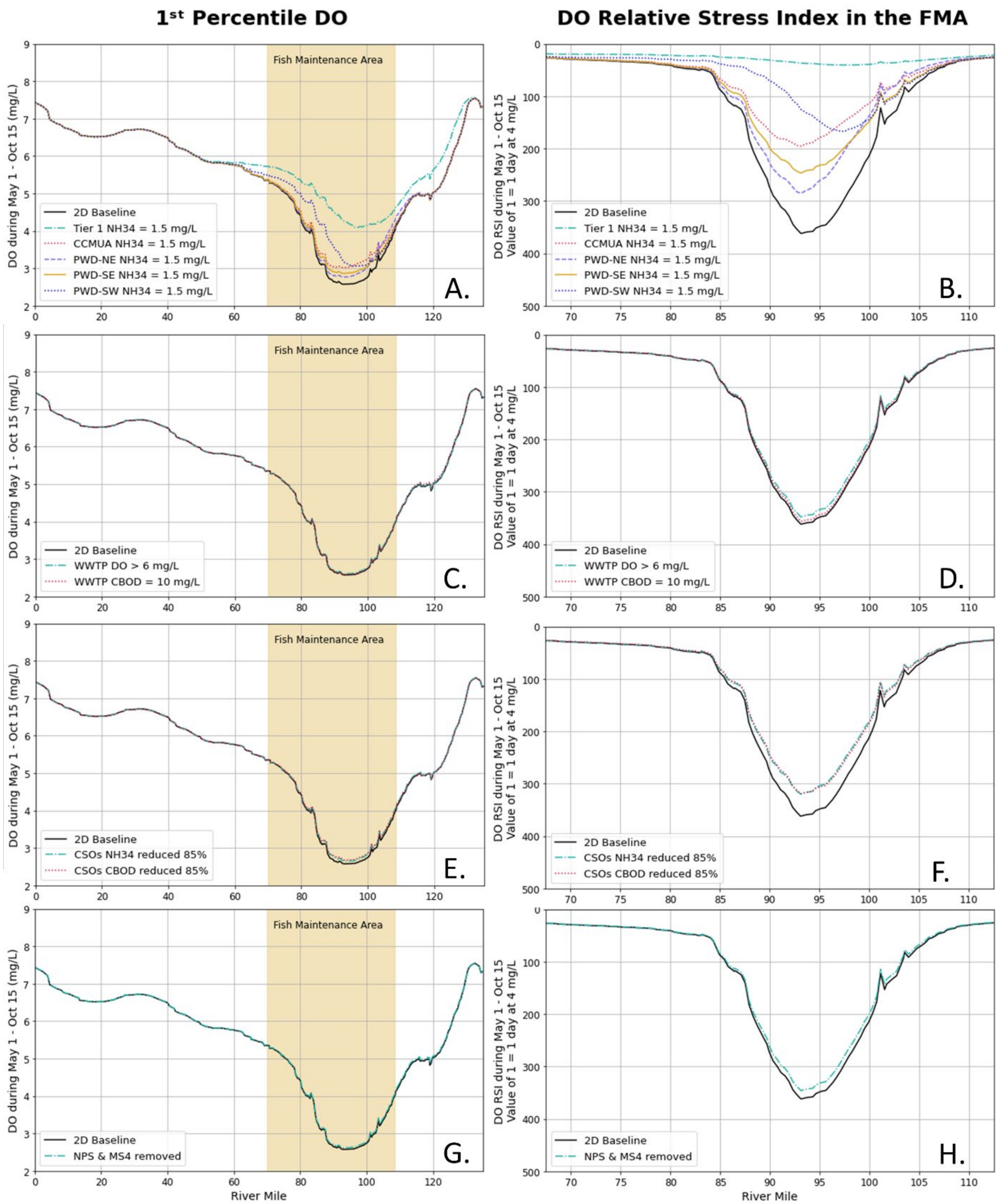
While model predictions of specific DO values contain inevitable uncertainty, there is considerably less uncertainty in the *relative* predictions between multiple scenarios. In other words, the model is more accurate in determining which pollutant loading scenario will produce the most favorable DO condition in the Estuary (and to what degree it will be more favorable), and less accurate in characterizing the absolute DO concentrations for any particular scenario. To leverage the strengths of the water quality model while mitigating its uncertainty, the Commission developed a semi-empirical method to combine model output with observed gage data to estimate a restored DO condition. For an in-depth discussion of this semi-empirical method and how it reduces model uncertainty, see Appendix A.

3. FACTORS THAT CAN IMPROVE DISSOLVED OXYGEN IN THE FISH MAINTENANCE AREA

3.1 SENSITIVITY OF SOURCE CATEGORIES

A series of 2D model sensitivity test scenarios were designed to evaluate which pollutant sources to the Estuary may substantially impact DO improvement in the FMA. The following source categories were evaluated: individual wastewater discharges (NH34, TN, CBOD, DO), CSOs (NH34, CBOD), non–point sources, municipal separate storm sewer systems (MS4s), and source contributions from major tributaries including the non-tidal mainstem Delaware River (C, N, and P). Longitudinal results for 1st percentile DO and DO Relative Stress Index (see Section 0) from each sensitivity scenario were compared against results from the 2D baseline scenario (Figure 3-1). Table 3-1 summarizes findings from the sensitivity tests described below.

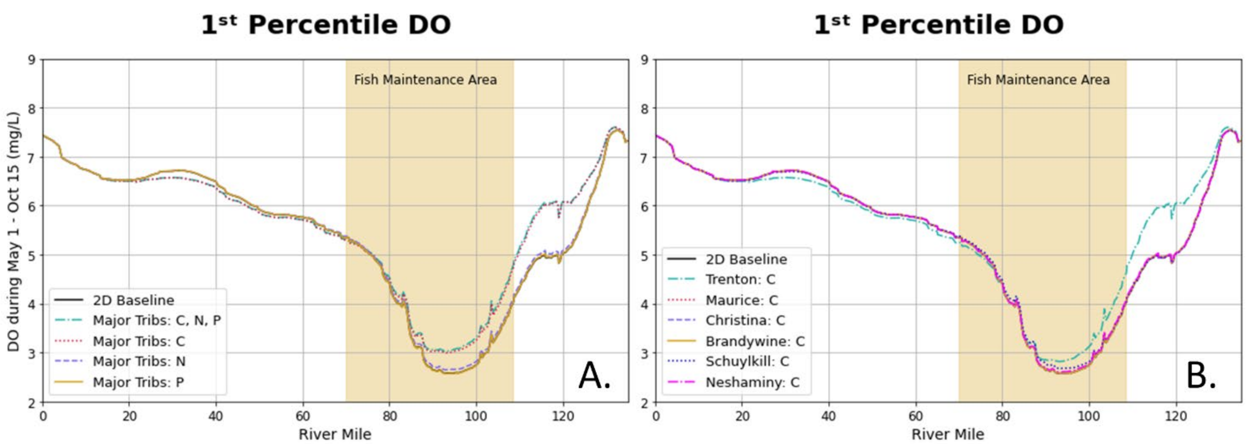
- **Ammonia from individual wastewater discharges:** Sensitivity test scenarios included reducing effluent ammonia to 1.5 mg/L for the four largest discharges individually (PWD Southwest WPCP, PWD Northeast WPCP, PWD Southeast WPCP, and Camden County MUA) and for the 12 Tier 1 discharges together (Figure 3-1 A,B). Reducing effluent ammonia loads from these discharges resulted in substantial DO improvement in the FMA. Further testing showed that reducing summer ammonia loads alone contributed to this effect; reducing winter ammonia loads did not measurably improve DO in the FMA. Section 3.2 describes further efforts to evaluate individual wastewater discharges.
- **DO, CBOD, and TN from individual wastewater discharges:** For all wastewater discharges included in the model, effluent DO was set to a minimum value of 6 mg/L and, independently, CBOD was decreased to 10 mg/L (Figure 3-1 C,D). Increasing effluent DO had a modest beneficial impact on DO in the FMA, while decreasing CBOD did not have a substantial impact. Limiting effluent TN to 4 mg/L did not provide additional benefit to DO in the FMA relative to only reducing ammonia levels (while keeping TN constant).
- **Ammonia and CBOD from CSOs:** Reducing ammonia and CBOD concentrations by 85% in CSO inflows to the Estuary resulted in modest improvements to DO in the FMA (Figure 3-1 E,F). Decreasing these concentrations by 85% was intended as a sensitivity test, not a realistic reduction scenario. Expected reductions from CSO long term control plans were implemented in the restored scenario described in Section 5.
- **Non–point sources (NPS) and municipal separate storm sewer systems (MS4):** Removing nitrogen and carbon from NPS and MS4 runoff did not result in substantial improvement to DO in the FMA (Figure 3-1 G,H).



Results from sensitivity tests are compared to the 2D baseline scenario. Individual wastewater discharge NH34 reduced to 1.5 mg/L (A,B). DO set to a minimum of 6 mg/L and CBOD set 10 mg/L for all modeled wastewater discharges (C,D). CSO ammonia and CBOD reduced by 85% (E,F). N and C from NPS and MS4 eliminated (G,H).

Figure 3-1: Source category sensitivity tests

- **Nutrient loads from tributaries:** Nutrient concentrations from the six largest tributary boundaries (Delaware River at Trenton, Schuylkill River, Christina River, Brandywine Creek, Neshaminy Creek, and Maurice River) were reduced to minimal concentrations. Reduced nitrogen (N) and phosphorus (P) loads from these tributaries did not have a substantial impact on DO in the FMA (Figure 3-2A). The low-DO response to reduced tributary carbon (C) is due almost entirely to impact from the Delaware River at Trenton, with carbon from the Schuylkill River contributing a minor impact (Figure 3-2B). It is important to note that these tributary carbon impacts are due to the large flows at these boundaries; the carbon concentrations are reflective of background conditions and would not be subject to regulatory control.



A. Four test scenarios where C, N, and/or P from six major tributaries (Delaware River at Trenton, Schuylkill River, Maurice River, Christina River, Brandywine Creek, and Neshaminy Creek) were set to minimal values.
B. Six test scenarios where C was reduced from each major tributary individually.

Figure 3-2: Tributary load sensitivity tests

Table 3-1: Summary of 2D source sensitivity results

Factors that can most improve DO in the FMA	Factors that can slightly improve DO in the FMA	Factors that cannot measurably improve DO in the FMA
Summer (May–Oct) ammonia loads from specific point source discharges Carbon loads from Delaware River at Trenton	Combined sewer overflows (CSOs) DO concentration in treated effluent from the largest point source discharges Carbon loads from Schuylkill River	Nutrient (C, N, P) loads from tributaries, except C loads from Delaware River at Trenton and Schuylkill River Winter (Nov–Apr) ammonia, CBOD, and TN from all point source discharges Summer (May–Oct) ammonia loads from many point source discharges Direct stormwater runoff into the Estuary

3.2 Classification of Wastewater Discharges

3.2.1 Wastewater Discharge Screening using 2D Model

The nineteen wastewater discharges with the largest summer ammonia loads were selected for screening analysis (Table 3-2). A 2D model scenario was developed for each of these discharges in which the effluent from the individual discharge only was modeled with a maximum ammonia concentration of 1.5 mg/L. TN was kept constant by adding the difference between the original ammonia concentration and 1.5 mg/L to nitrate. No other adjustments were made. Three metrics were developed to evaluate the individual impact of each discharge's effluent ammonia concentration on DO in the Estuary:

- **Summer ammonia load**: The ammonia load from each discharge was calculated as the product of the discharge's permitted flow and the seasonal median effluent ammonia concentration (Table 2-1). The nine largest ammonia discharges, which contribute 95% of the total load to the Delaware Estuary, were selected for further analysis in the 3D model (Table 3-2).
- **Volume with ΔDO > 1 mg/L**: The extent of each discharge's impact within the total volume of the Estuary was evaluated with this metric. At each model cell, the difference between scenario DO and baseline DO was determined. Only time steps where the baseline DO was ≤ 7 mg/L and the DO difference was > 0.05 mg/L were considered. In each cell, the average DO difference was weighted by the cell's median volume and resulting values for all cells were summed to yield the equivalent volume in the Delaware Estuary where the DO increased by at least 1 mg/L. Discharges that impacted a volume > 100,000 m^3 according to this metric were selected for further analysis in the 3D model (Table 3-2).
- **Percent Reduction in DO Stress within FMA**: For each scenario, the total DO Stress in the FMA was calculated by summing the DO Relative Stress Index (RSI) for each cell in the FMA (see Section 2.5.3). Discharges that reduced DO RSI in the FMA by > 5% were selected for further analysis in the 3D model (Table 3-2).

Table 3-2: Screening results for the 19 wastewater discharges with the greatest ammonia load

Values that warrant further analysis are highlighted with bold text. Discharges with a highlighted value in any column were selected.

Point Source Name	Summer NH34 Load (kg N/day)	% Cumulative NH34 Load	Vol. with ΔDO > 1 mg/L (m^3)	% Reduction DO RSI in FMA
PWD Southwest WPCP	**14354**	**36.5%**	**3.16E+08**	**51.7%**
Camden County Municipal Utilities Authority	**5241**	**49.9%**	**1.38E+08**	**36.9%**
City of Wilmington WWTP	**4807**	**62.1%**	**6.98E+07**	1.3%
PWD Southeast WPCP	**3626**	**71.4%**	**7.92E+07**	**25.2%**
PWD Northeast WPCP	**3535**	**80.4%**	**7.80E+07**	**20.4%**
Gloucester County Utilities Authority	**2438**	**86.6%**	**4.45E+07**	**10.6%**
Hamilton Twp WPCF	**1634**	**90.7%**	**5.24E+07**	2.6%
DELCORA	**1014**	**93.3%**	4.73E+04	0.8%
Lower Bucks County Joint Municipal Authority	**747.6**	**95.2%**	**1.71E+07**	1.8%
City of Millville Sewage Treatment Authority	495.4	96.5%	**1.95E+06**	0.3%
Trenton Sewer Utility	411.2	97.5%	**1.10E+07**	1.0%
Morrisville Borough Municipal Authority	261.8	98.2%	**8.68E+06**	0.9%
Cumberland County Utilities Authority	124.7	98.5%	0.00E+00	0.0%
Cinnaminson Sewerage Authority	120.8	98.8%	**2.69E+06**	0.8%
Willingboro WPCP	96.8	99.1%	0.00E+00	0.3%
Logan Township Municipal Utilities Authority	66.9	99.2%	0.00E+00	0.0%
Florence Township Sewage Treatment Plant	56.2	99.4%	3.87E+01	0.3%
Penns Grove Sewerage Authority	55.4	99.5%	0.00E+00	0.3%
Beverly Sewerage Authority	54.9	99.7%	0.00E+00	0.2%

3.2.2 Sequential Testing of Discharges using 3D Model

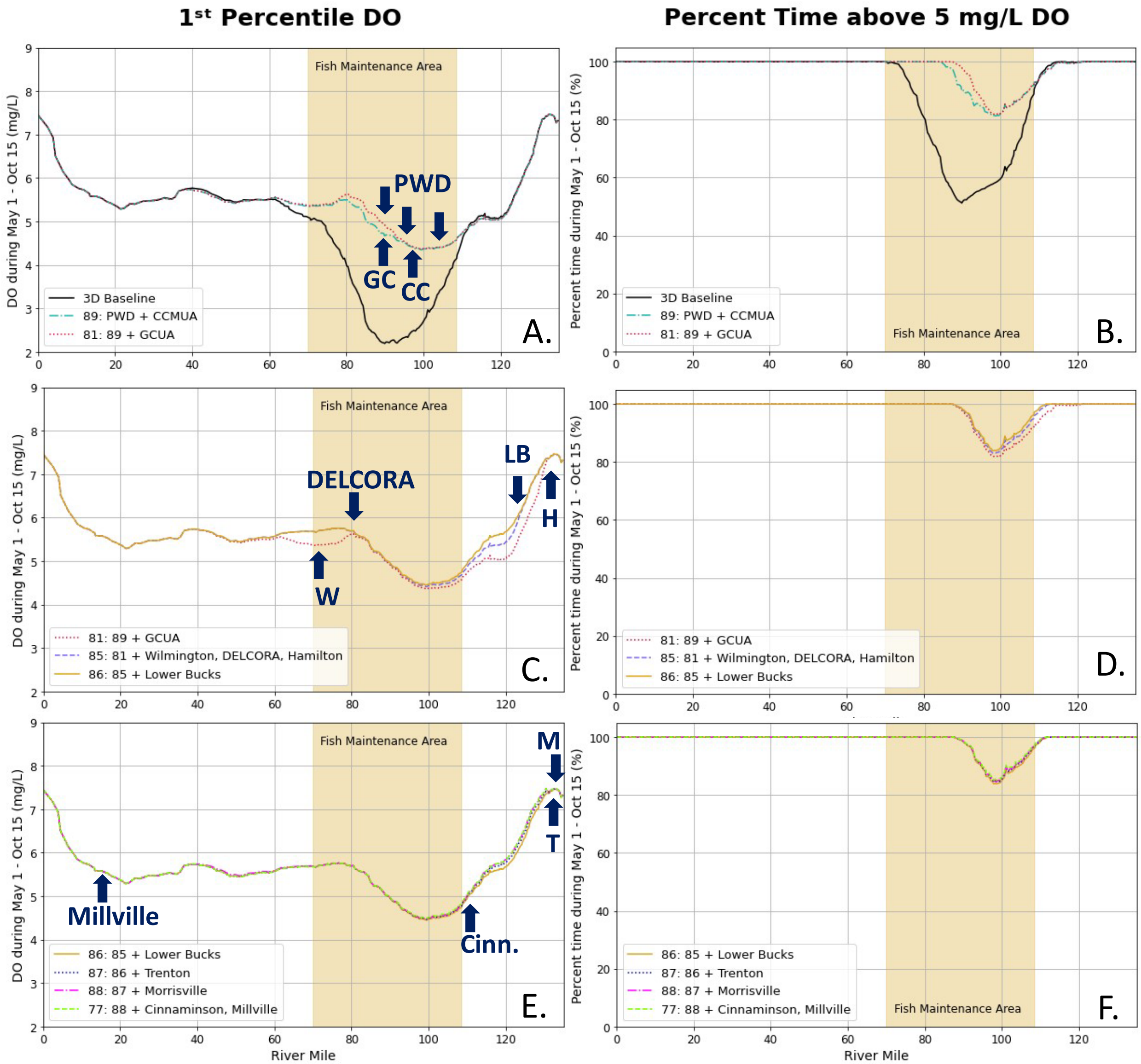
The thirteen (13) point source wastewater discharges identified for further analysis from 2D model testing (Table 3-2) were included in a sequence of 3D model test scenarios to evaluate the cumulative impact on low DO in the Estuary of reducing their ammonia discharge concentrations. Table 3-3 lists a subset of scenarios that were part of this analysis; for each scenario, ammonia concentrations in one or more discharge(s) were reduced in combination with the ammonia reductions in the previous scenario in the sequence. Figure 3-3 shows 1st percentile DO and percent time above 5 mg/L for the scenarios in Table 3-3. Results from these cumulative scenarios were used to identify how strongly each discharge impacts low DO and DO improvement in the FMA.

- PWD Southwest, PWD Southeast, PWD Northeast, and Camden County MUA (Run 89). These four discharges are located between RM 90 and RM 104, in the heart of the "DO sag." They have a large impact on low DO in the FMA. Reducing effluent ammonia to 1.5 mg/L for these four discharges increases the minimum 1st percentile DO by ~2 mg/L relative to the baseline scenario (Figure 3-3A) and results in DO staying above 5 mg/L at least 80% of the time throughout the Estuary (Figure 3-3B).
- Gloucester County UA (GCUA) (Run 81). Reducing effluent ammonia from GCUA to 1.5 mg/L as well brings additional benefit to low DO in the FMA relative to Run 89 (Figure 3-3A). Both 1st percentile DO and percent time above 5 mg/L show substantial improvement over RM 80–95 (Figure 3-3B).
- City of Wilmington WWTP and Delaware County Regional Water Quality Control Authority (DELCORA) (Run 85). These two discharges are located at the downstream end of the FMA DO sag, between RM 70 and RM 80. Reducing their effluent ammonia to 1.5 mg/L along with the previous five discharges results in additional benefit to low DO in this part of the FMA, with 1st percentile DO increasing 0.2 to 0.3 mg/L relative to Run 81 (Figure 3-3C). Note that percent time above 5 mg/L does not show a benefit from the ammonia reductions at these two discharges because in Run 81 DO is always above 5 mg/L in this part of the FMA (Figure 3-3D).
- **Hamilton Twp WPCF and Lower Bucks Joint MA (Runs 85 and 86).** These discharges are located upstream of the FMA. Reducing their effluent ammonia to 1.5 mg/L along with the previous seven discharges has the biggest impact on low DO in Zone 2, near RM 120, though the impacts carry downstream into the FMA; this is especially apparent in terms of percent time above 5 mg/L in the upper FMA (Figure 3-3D).
- **Trenton Sewer Utility, Morrisville Borough MA, Cinnaminson Sewerage Authority, and City of Millville Sewage Treatment Authority (Runs 77, 87, and 88).** These discharges are located outside of the FMA. Reducing their effluent ammonia to 1.5 mg/L does not have a measurable impact on low DO in the FMA relative to Run 86 (Figure 3-3E,F).

Table 3-3: A subset of sequential 3D model scenarios that were tested

For each scenario, effluent ammonia was reduced to 1.5 mg/L for the discharges listed. Discharge names in bold italics indicate that these discharges were added to those simulated with reduced effluent ammonia from the previous run. Results from these runs are shown on Figure 3-3.

Run #	Discharges with effluent ammonia = 1.5 mg/L
3D baseline	None
89	PWD Southwest WPCP, PWD Southeast WPCP, PWD Northeast WPCP, Camden County MUA
81	PWD Southwest WPCP, PWD Southeast WPCP, PWD Northeast WPCP, Camden County MUA, ***Gloucester County UA***
85	PWD Southwest WPCP, PWD Southeast WPCP, PWD Northeast WPCP, Camden County MUA, Gloucester County UA, ***City of Wilmington WWTP, DELCORA, Hamilton Twp WPCF***
86	PWD Southwest WPCP, PWD Southeast WPCP, PWD Northeast WPCP, Camden County MUA, Gloucester County UA, City of Wilmington WWTP, DELCORA, Hamilton Twp WPCF, ***Lower Bucks Joint MA***
87	PWD Southwest WPCP, PWD Southeast WPCP, PWD Northeast WPCP, Camden County MUA, Gloucester County UA, City of Wilmington WWTP, DELCORA, Hamilton Twp WPCF, Lower Bucks Joint MA, ***Trenton Sewer Utility***
88	PWD Southwest WPCP, PWD Southeast WPCP, PWD Northeast WPCP, Camden County MUA, Gloucester County UA, City of Wilmington WWTP, DELCORA, Hamilton Twp WPCF, Lower Bucks Joint MA, Trenton Sewer Utility, ***Morrisville Borough MA***
77	PWD Southwest WPCP, PWD Southeast WPCP, PWD Northeast WPCP, Camden County MUA, Gloucester County UA, City of Wilmington WWTP, DELCORA, Hamilton Twp WPCF, Lower Bucks Joint MA, Trenton Sewer Utility, Morrisville Borough MA, ***Cinnaminson Sewerage Authority, City of Millville Sewage Treatment Authority***



Each discharge's approximate location is indicated with an arrow on the 1st percentile plot (left column).

Figure 3-3: 3D model results from sequential testing of effluent NH34 reductions

Based on these results, the 13 dischargers were divided into three classes that would each be tested as a group (Table 3-4, Figure 3-4). The classes are defined as follows:

- **Class A':** Discharges that have a major impact on low DO in the FMA. The biggest DO response to effluent ammonia reductions is located within the FMA, the discharge is located within the FMA, and low DO in the FMA is sensitive to the level of ammonia reduction.
- **Class A:** Discharges that have a marginal impact on low DO in the FMA. Low DO within the FMA is impacted, but the biggest DO response to effluent ammonia reductions is located outside of the FMA. The discharge is not located within the FMA, and low DO in the FMA is less sensitive to the level of ammonia reduction.
- **Class B:** Discharges that do not have a measurable impact on low DO in the FMA.

Table 3-4: Discharge classification results

Zone	River Mile	State	Point Source NPDES#	Point Source Name	Class
4	90.7	PA	PA0026671-001	PWD Southwest Water Pollution Control Plant	A'
3	97.9	NJ	NJ0026182-001A	Camden County Municipal Utilities Authority	
5	71.6	DE	DE0020320-001	City of Wilmington Wastewater Treatment Plant	
3	96.7	PA	PA0026662-001	PWD Southeast Water Pollution Control Plant	
3	103.9	PA	PA0026689-001	PWD Northeast Water Pollution Control Plant	
4	89.9	NJ	NJ0024686-001A	Gloucester County Utilities Authority	
4	80.4	PA	PA0027103-001	DELCORA	
2	121.9	PA	PA0026468-001	Lower Bucks County Joint Municipal Authority	A
2	128.4	NJ	NJ0026301-001A	Hamilton Twp Water Pollution Control Facility	
6	15.2	NJ	NJ0029467-001A	City of Millville Sewage Treatment Authority	B
2	131.8	NJ	NJ0020923-001A	Trenton Sewer Utility	
2	132.5	PA	PA0026701-201	Morrisville Borough Municipal Authority	
2	108.7	NJ	NJ0024007-001A	Cinnaminson Sewerage Authority	

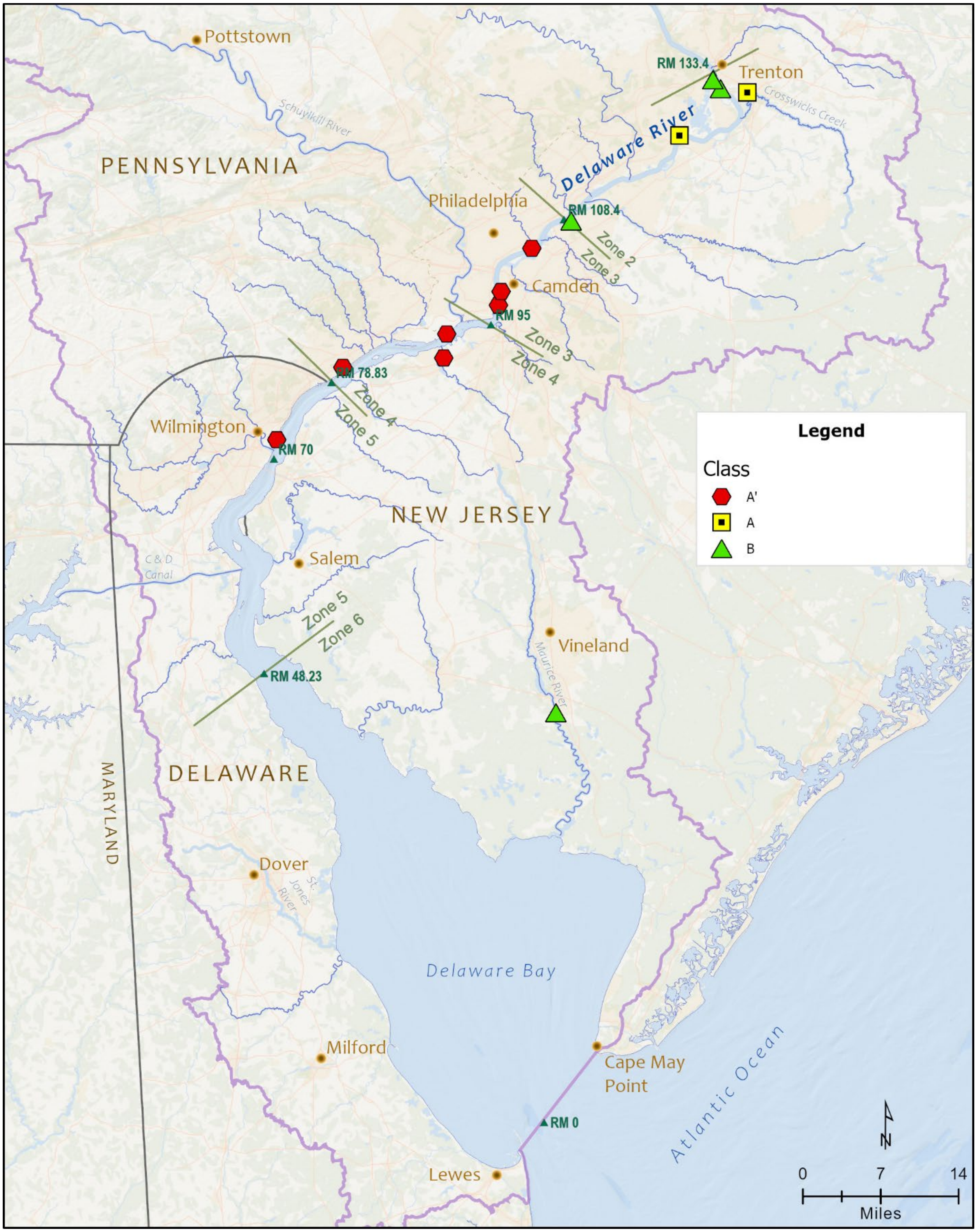


Figure 3-4: Locations of Class A', A and B point source discharges

4. RESTORATION ANALYSIS RESULTS

4.1 WASTEWATER NUTRIENT REDUCTION SCENARIOS

Candidate restoration analysis scenarios (referred to as "AA scenarios") were designed based on source sensitivity results (Section 3.1) and wastewater discharge classification (Section 3.2). As described in Section 2.3, the design condition that is the foundation for the restoration analysis scenarios represents existing water quality under critical conditions. Table 4-1 lists the AA wastewater nutrient (ammonia and total nitrogen) reduction scenarios that were prepared and simulated in the 3D model.

Table 4-1: Restoration analysis scenarios

Scenario ID	Description
AA01	3D baseline (design condition)
AA02	Class A' + A: Summer NH34 ≤ 10 mg/L
AA03	Class A' + A: Summer NH34 ≤ 5.0 mg/L
AA04	Class A' + A: Summer NH34 = 1.5 mg/L
AA05	Class A' + A: Summer TN ≤ 4.0 mg/L
AA06	All Tier 1: Summer NH34 = 1.5 mg/L
AA07	Class A' only: Summer NH34 = 1.5 mg/L
AA08	Class A': Summer NH34 = 1.5 mg/L Class A: Summer NH34 = 5 mg/L
AA10	Class A': Summer NH34 = 1.5 mg/L Class A: Summer NH34 = 10 mg/L

The AA scenarios differ only in: 1) which discharge classes were assigned reduced effluent nutrient concentrations; and 2) the level of reduction. For example, scenario AA02 caps summer ammonia at 10 mg/L for discharges in Classes A' and A. For each discharge in Classes A' and A, if the summer seasonal median ammonia (baseline value) is greater than 10 mg/L, ammonia was reduced to 10 mg/L and nitrate and CBOD were adjusted accordingly (Table 2-3). Whenever summer effluent ammonia was reduced, summer effluent DO was reduced to 2 mg/L or the discharge's existing permit limit (whichever is higher). As in the baseline design condition, NH34, NO3, CBOD, and DO were set to constant values for May through October. For these AA scenarios, CSOs were not adjusted from the baseline design condition and no reserve capacity was included.

Scenarios AA02 through AA05 test a range of nutrient effluent reduction scenarios for Classes A’ and A together. Figure 4-1 presents comparative results of these test scenarios and the baseline (AA01), showing: 1) 1st percentile DO, representing critically low values that DO is above 99% of the time; and 2) the percentage of time the DO is above 5 mg/L. For the baseline scenario, the minimum 1st percentile DO is 2.2 mg/L at RM 90 (Figure 4-1A); at the lowest point of the DO sag (RM 90), DO is above 5 mg/L 51% of the time (Figure 4-1B).

As the effluent ammonia from all Class A’ and A discharges was reduced from 10 mg/L (AA02) to 5 mg/L (AA03) to 1.5 mg/L (AA04), the minimum 1st percentile DO increases and moves upstream to 2.9 mg/L (RM 96), 3.4 mg/L (RM 96), and 4.0 mg/L (RM 98), respectively (Figure 4-1A). Wastewater ammonia levels need to be reduced to 1.5 mg/L before DO in the FMA remains consistently above 4 mg/L. Similarly, minimum percent time above 5 mg/L increases from 51% (AA01) to 59% (AA02), 63% (AA03), and 74% (AA04), and the spatial extent that experiences DO less than 5 mg/L decreases from 50 mi (AA01) to 37.5 mi (AA02), 33 mi (AA03), and 28 mi (AA04) (Figure 4-1B). Technically feasible reductions in effluent ammonia to 1.5 mg/L have a measurable and significant benefit towards achieving improved DO in the FMA.

In scenario AA05, reducing the total nitrogen (TN) to 4 mg/L (with NH34 = 1.5 mg/L) provides almost identical results to scenario AA04 (Figure 4-1A,B). While reducing total nitrogen to 4 mg/L is feasible, it provides no measurable benefit to DO improvement in the FMA; as a result, this candidate scenario was eliminated from further consideration.

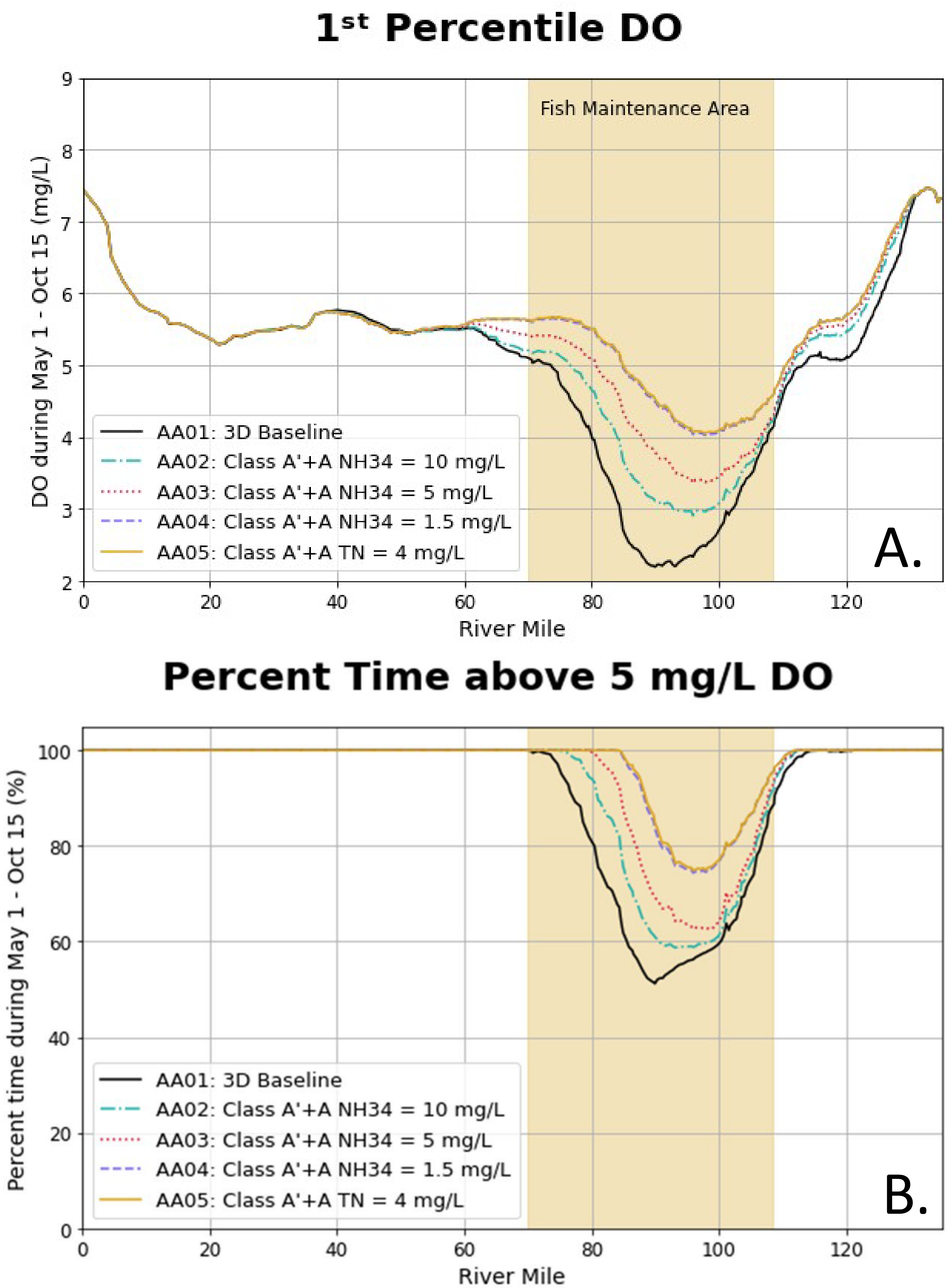


Figure 4-1: Restoration analysis results for scenarios AA01–AA05

Figure 4-2 compares scenarios AA04, AA06, and AA07, which simulate reductions in effluent ammonia concentrations to 1.5 mg/L for the following groups of candidate discharges:

- AA07: The seven (7) wastewater discharges identified as Class A' that have a major impact on low DO in the FMA.
- AA04: The nine (9) wastewater discharges identified as Class A' and Class A.
- AA06: The twelve (12) wastewater discharges originally identified as "Tier 1" discharges (section 2.3.3), which were included in the Kleinfelder cost study (DRBC, 2021).

Compared to Scenario AA07 that simulated reduced ammonia concentrations in the seven Class A' discharges only, reducing ammonia concentrations from the two Class A discharges as well (AA04) brings measurable improvement in low DO and percent of time above 5 mg/L to the upper FMA. However, including the three remaining Tier 1 discharges (AA06) does not bring additional benefit over Scenario AA04. These results support including Class A and A' discharges and eliminating other point source discharges from future consideration.

Scenarios AA04, AA07, AA08, and AA10 represent a range of effluent ammonia reduction scenarios for Class A discharges (Table 4-1; Figure 4-3). In each scenario, the Class A' discharges have effluent ammonia concentrations set to 1.5 mg/L. There is a benefit to low DO from reducing effluent ammonia concentrations for Class A discharges; this is demonstrated in scenarios AA04, AA08, and AA10 that have minimum 1st percentile DO that is approximately 0.1 mg/L higher than AA07 in the FMA and a spatial extent experiencing DO < 5 mg/L that is about 10 mi less than AA07. However, DO improvement in the FMA is less sensitive to the level of ammonia reduction for the Class A discharges. Reducing Class A effluent ammonia to 10, 5 or 1.5 mg/L increases the minimum 1st percentile DO by 0.05, 0.06 and 0.08 mg/L, respectively, relative to AA07. Appendix B contains additional longitudinal plots showing the 1st, 10th, 25th, and 50th percentiles of DO, as well as percent time over 4, 5, 6, and 7 mg/L from the groups of AA scenarios presented in Figure 4-1, Figure 4-2, and Figure 4-3.

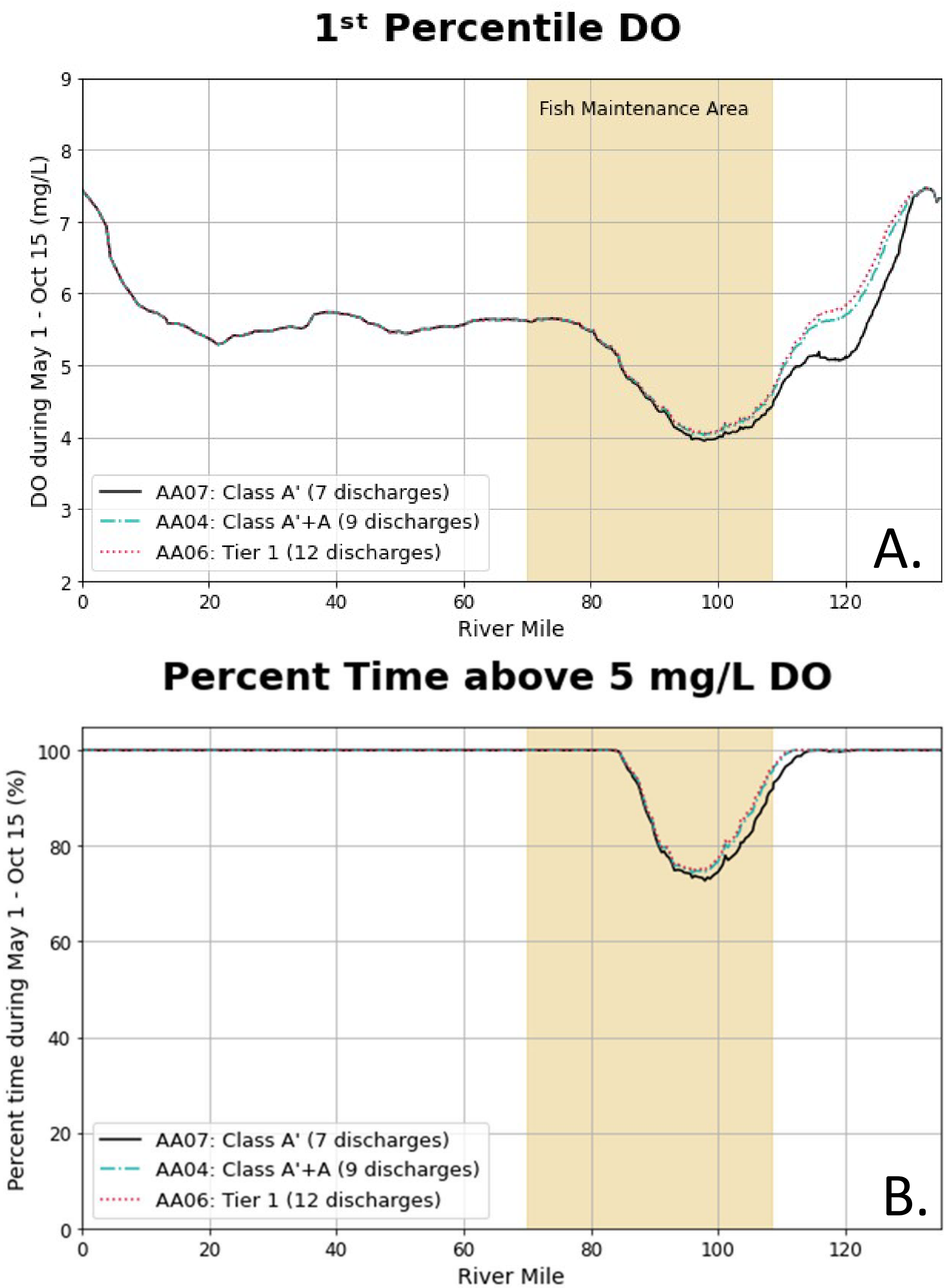


Figure 4-2: Restoration analysis results for scenarios AA04, AA06, and AA07

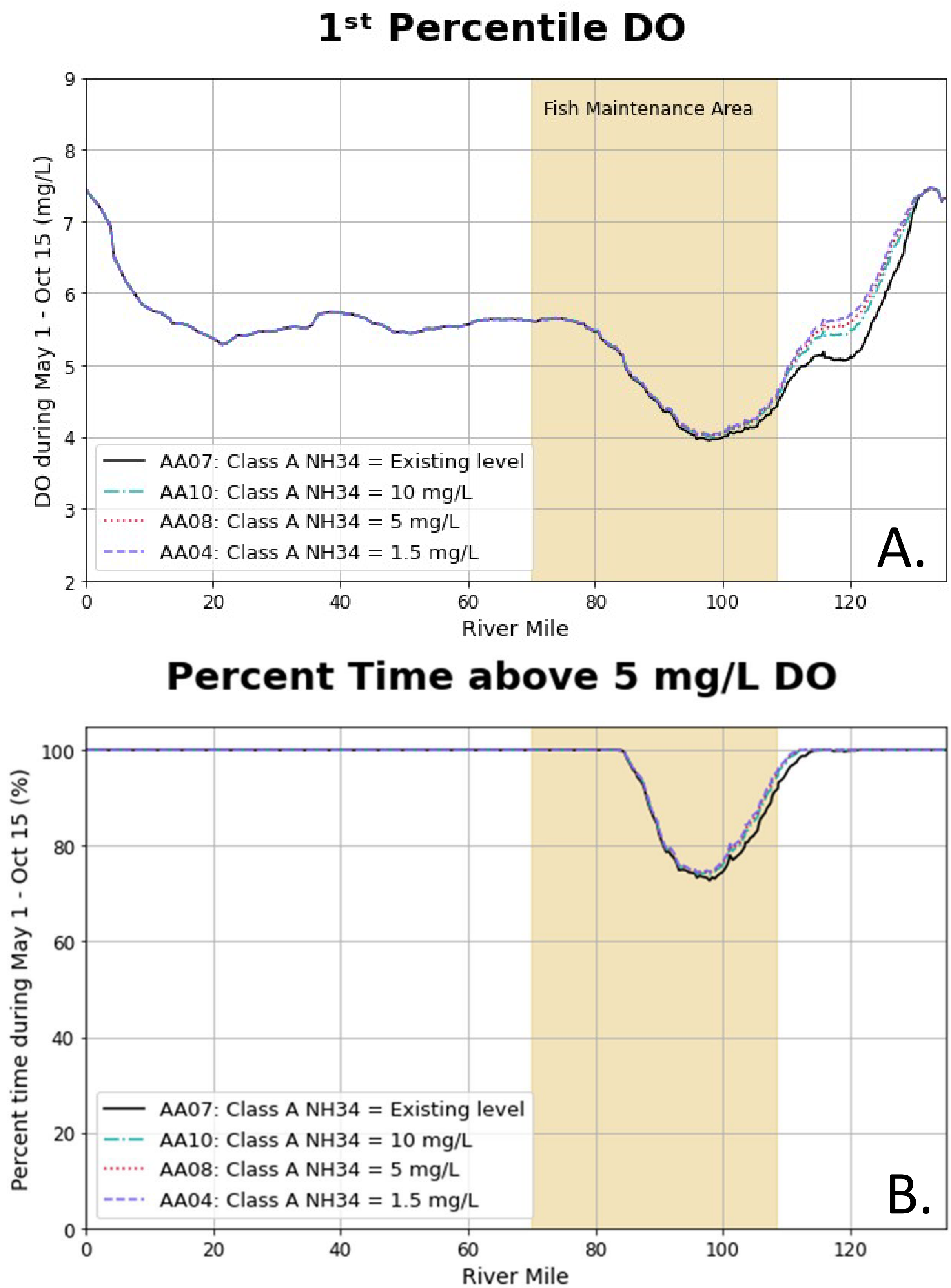


Figure 4-3: Restoration analysis results for scenarios AA04, AA07, AA08 and AA10

4.2 Wastewater Treatment Costs and DO Improvements

An analysis of costs versus DO improvements is shown in Figure 4-4. Costs are presented as annualized present value in 2019 dollars and are taken directly from the feasibility and cost study (DRBC, 2021) as applied to each restoration analysis scenario. The DO improvement between the baseline (AA01) and each scenario varies in time and space but is distilled into a single value by plotting the maximum improvement in the 1st percentile DO within the FMA. This metric was obtained by calculating the difference in 1st percentile DO at every longitudinal cell (i.e., RM coordinate) within the FMA, and then taking the maximum of those differences.

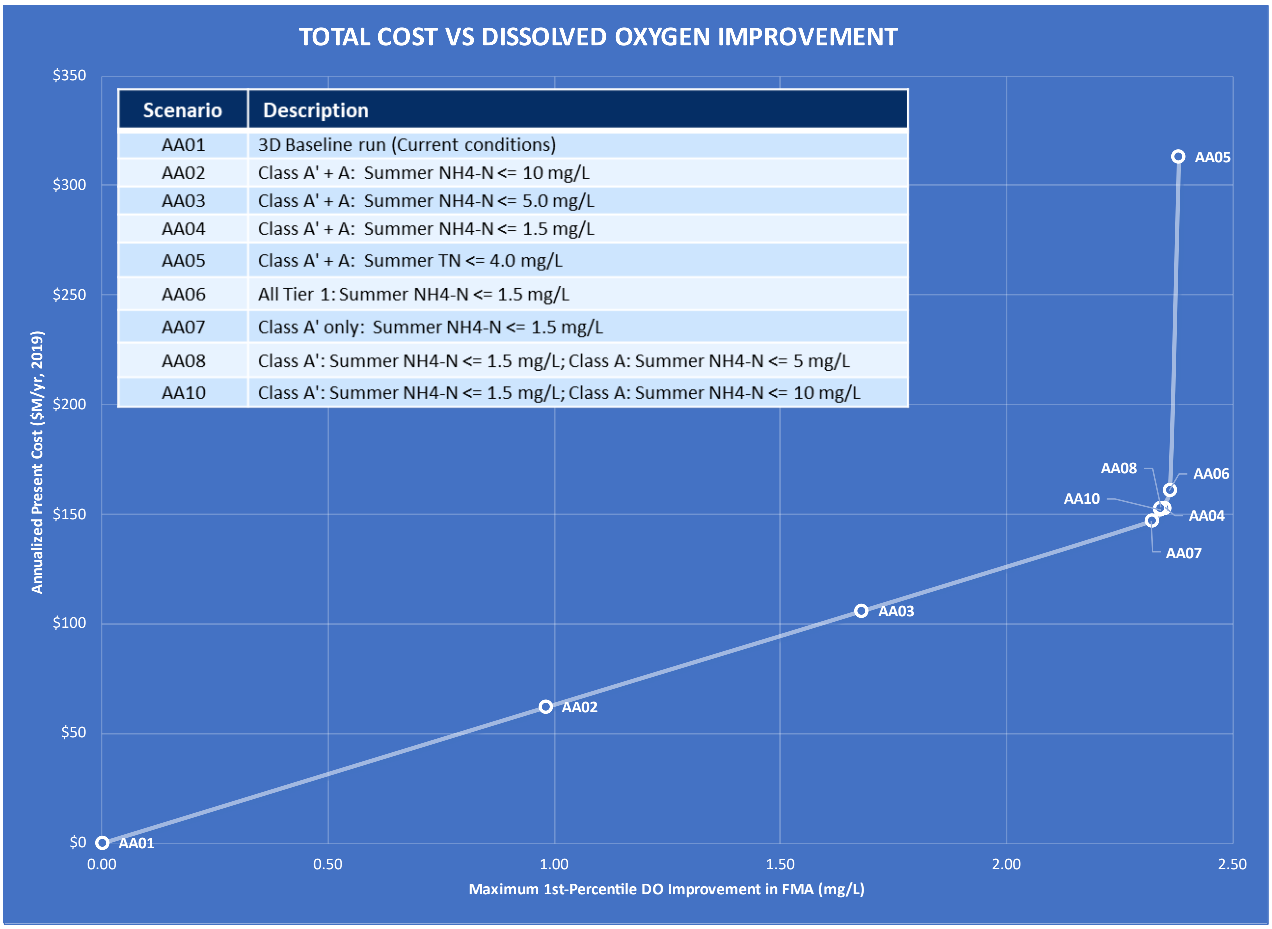


Figure 4-4: Cost versus DO improvement within the FMA for each AA scenario

The resultant curve in Figure 4-4 shows a linear improvement in DO as wastewater ammonia concentrations decrease, and then a sharp inflection point going from an ammonia concentration of 1.5 mg/L to a total nitrogen concentration of 4.0 mg/L. This reflects the fact that, after reducing ammonia to the practical limit of technology through nitrification, removing nitrate would incur a high cost with no improvement in DO (AA05). Overall, this systemwide characterization of cost versus DO improvement points to the inflection point as the region where infrastructure investments can yield a significant benefit in terms of enhanced DO in the FMA. There are several AA scenarios clustered near the inflection point, which are discussed in Section 4.3 below.

4.3 Inflection Scenario

Scenarios AA04, AA06, AA07, AA08, and AA10 are clustered around the inflection point, which essentially represents the point of vanishing returns in terms of infrastructure investment. Scenarios AA06 and AA07 differ in the number of discharges simulated at 1.5 mg/L ammonia; AA07 includes reduced ammonia from only the seven Class A' dischargers, while AA06 includes reduced ammonia from all twelve Tier 1 discharges. Scenarios AA04, AA08, and AA10 simulate the seven Class A' discharges at 1.5 mg/L ammonia and the two Class A discharges at ammonia levels of 1.5, 5.0 and 10 mg/L, respectively. Since the Class A discharges are both in Zone 2, upstream of the FMA, it makes sense to evaluate these scenarios at the region of the FMA where they exert their greatest impact, namely the most upstream transect of the FMA (i.e., the most upstream transect in Zone 3). Figure 4-5 does just that, plotting the annualized cost against the improvement in 1st percentile DO at the most upstream transect within the FMA.

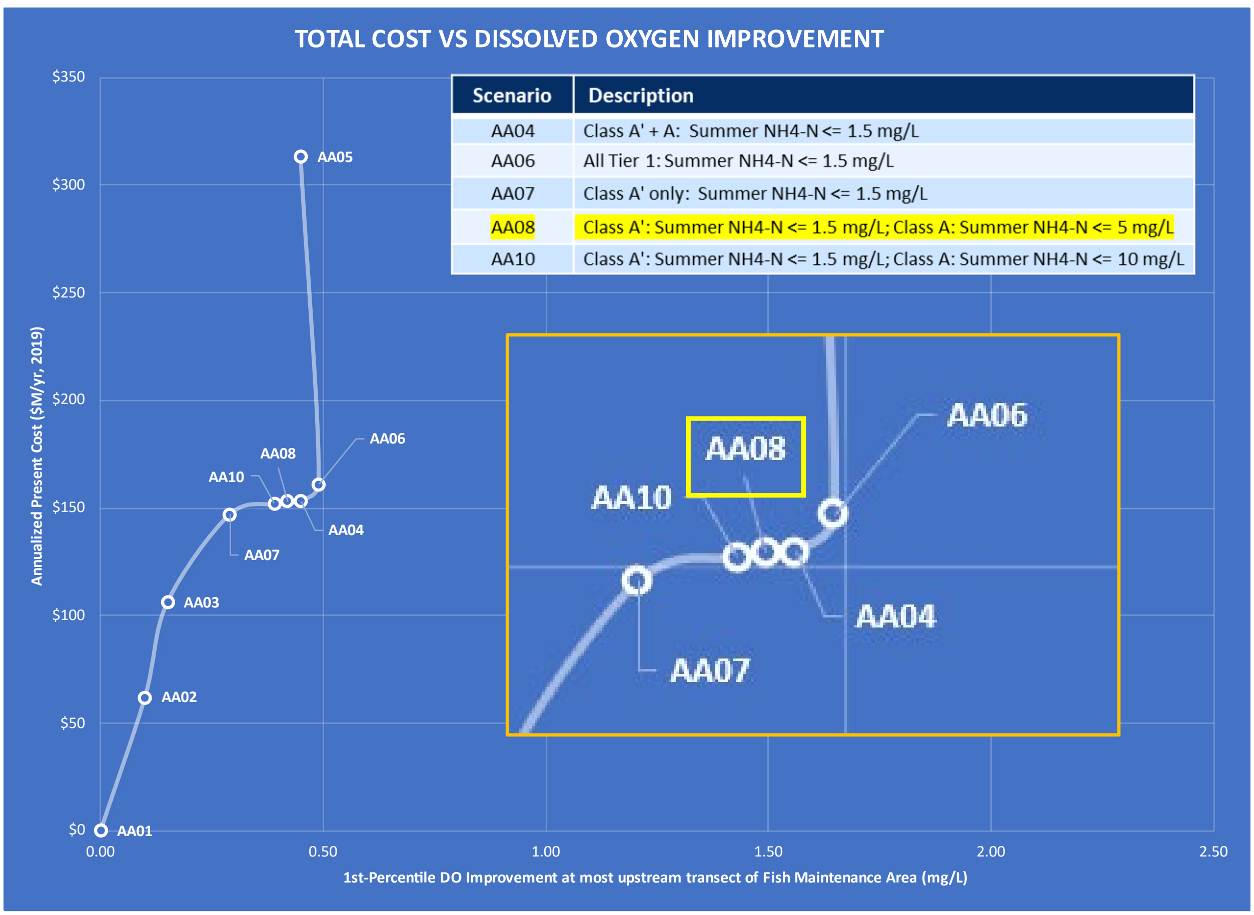


Figure 4-5: Cost versus DO improvement at upstream-most transect in the FMA for each AA scenario

Notice that the overall magnitude of DO improvement is smaller in the most upstream transect (Figure 4-5) compared to the transect with the maximum improvement (Figure 4-4), which occurs near the center of the FMA where the current DO sag is largest. Also notice that under scenario AA07, in which only the seven Class A' discharges are simulated with a reduced ammonia concentration of 1.5 mg/L, significant additional DO improvement at this transect in the FMA could be achieved for a relatively small investment on a systemwide basis. The opposite is true for scenario AA06, which simulates all 12 Tier 1 discharges with ammonia at 1.5 mg/L. Clearly this scenario lies on the vertical portion of the curve, in which costs increase quickly with no incremental improvement in DO.

This leaves scenarios AA04, AA08, and AA10, which differ only in the effluent concentrations assumed for the two Class A discharges. Both the DO differences and the cost differences among these scenarios are not significant. DRBC selected loading scenario AA08, in which the two Class A discharges in Zone 2 are assigned ammonia concentrations of 5.0 mg/L, as the “inflection scenario” to evaluate further as a possible pathway for restoration because, by its position between scenarios AA04 and AA10 on the curves in Figure 4-4 and Figure 4-5, it represents the center of the inflection point.

Implementation of the wastewater load reductions simulated in inflection scenario AA08 would result in an overall future ammonia load reduction of 87% (based on design conditions) from the nine wastewater discharges that would be impacted (the Class A' plus A facilities), as shown in Table 4-2. It is important to recognize that the inflection scenario, and the resultant restoration scenario described in Section 5, were based solely on technological feasibility, natural conditions, and the sensitivity of DO improvement to further load reduction. Cost and affordability were both quantified and considered, but no socio-economic constraints drove the selection of the inflection scenario. Technological feasibility also played a minimal role, as the impact on DO from further ammonia reductions, even if they were possible, would be minimal. However, due to conservative model assumptions, model uncertainty, and other contributing factors that may not have been considered in this analysis, the inflection and restoration scenarios do not necessarily represent the greatest possible improvement to DO in the FMA.

Table 4-2: Ammonia load reductions under design conditions

Wastewater Discharge	Summer Ammonia Load (kg/day)		
	Baseline Scenario	**Inflection Scenario (AA08)**	**Percent Reduction**
PWD Southwest WPCP	14,400	1,140	92%
Camden County MUA	5,240	454	91%
City of Wilmington WWTP	4,810	761	84%
PWD Southeast WPCP	3,630	636	83%
PWD Northeast WPCP	3,540	1,190	66%
Gloucester County UA	2,440	153	94%
Hamilton Twp WPCF	1,630	91	94%
DELCORA	1,010	397	61%
Lower Bucks County Joint MA	748	57	92%
Total	37,448	4,879	87%

4.4 SOCIO-ECONOMIC EVALUATION

DRBC evaluated the socio-economic factors affecting the attainment of uses, as required by Resolution No. 2017-4. Details of the affordability evaluation are documented in a separate report entitled *Social and Economic Factors Affecting the Attainment of Aquatic Life Uses in the Delaware River Estuary* (DRBC, 2022b).

During 2022, DRBC became aware that DELCORA sought to increase the permitted flow of its plant to 70 MGD. DRBC commissioned Kleinfelder to develop an addendum to its 2021 report (DRBC, 2021) with updated cost estimates for DELCORA reflecting the proposed permitted flow (Kleinfelder, 2022). Although the currently (as of August 2024) permitted flow for DELCORA is 44 MGD, the socio-economic evaluation utilized the updated cost estimate for DELCORA based on the 70-MGD permitted flow anticipated in 2022. The effluent levels assumed for Tier 1 Utilities and annualized costs (in $M, 2019 dollars) are shown in Table 4-3.

Table 4-3: Annualized cost in 2019 $M/yr to achieve reduced effluent levels

Utility	New Effluent Concentration			
	Ammonia 10 mg/L	Ammonia 5 mg/L	Ammonia 1.5 mg/L	Total Nitrogen 4 mg/L
Wilmington	6	20	26	49
CCMUA	12	15	18	35
City of Trenton	0.1	2	3	6
Hamilton Twp WPCF	3	4	4	7
Willingboro WPCF	0	0	2	3
DELCORA	4	11	14	27
Morrisville	2	2	3	5
LBCJMA	2	2	2	5
GCUA	3	4	5	11
PWD (SW, SE, & NE)	32	50	84	179

Two guidance documents were utilized to evaluate the social and economic impact of these potential costs on the affected communities.

- EPA. *Proposed 2022 Clean Water Act Financial Capability Assessment Guidance*. February 2022.
- Raucher et al. *Developing a New Framework for Household Affordability and Financial Capability Assessment in the Water Sector*. For AWWA, NACWA, WEF. April 17, 2019.

Although numerous metrics were evaluated as part of the overall socio-economic evaluation, two key resulting affordability metrics are presented: the Household Affordability (HA) metric from the utility association (American Water Works Association [AWWA], National Association of Clean Water Agencies [NACWA], and Water Environment Federation [WEF]) guidance and the Residential Indicator (RI) from the EPA guidance. These two metrics allow for the comparison of different future scenarios to each other and to the baseline. All results are presented by utility service area. The affordability burden factors presented here should not be interpreted as a service area rate study. Final costs to taxpayers or rate payers will depend upon many factors, including the availability and use of federal, state, and local programs that can improve affordability for utilities, communities, and individual households.

The combined total annualized cost for the wastewater improvements recommended in scenario AA08 equals $153M/yr in 2019 dollars, which includes the annualized present worth of $2.6B of capital investment as well as annual operation and maintenance. As shown in Table 4-4 below, for scenario AA08 neither indicator shows a change to the burden category compared to the baseline. While significant costs are associated with scenario AA08, and these costs are assumed to be distributed among ratepayers, the associated increase to ratepayers is not enough to increase the baseline burden category, as defined by either guidance document, to a higher category. By comparison, scenarios AA05 and AA06 do show a change to the burden category for PWD (AA05) and Morrisville and Willingboro (AA06) beyond the baseline burden category (AA01).

Table 4-4: Affordability metric categories for AA scenarios

Utility Name	Metric	AA01	AA02	AA03	AA04	AA05	AA06	AA07	AA08
CCMUA	HA	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden
	RI	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE
City of Trenton	HA	Moderate-High Burden	Moderate-High Burden	Moderate-High Burden	Moderate-High Burden	Moderate-High Burden	Moderate-High Burden	Moderate-High Burden	Moderate-High Burden
	RI	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE
DELCORA	HA	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden
	RI	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE
GCUA	HA	Low Burden	Low Burden	Low Burden	Low Burden	Low-Burden	Low Burden	Low Burden	Low Burden
	RI	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW
Hamilton Twp WPCF	HA	Low Burden	Low Burden	Low Burden	Low Burden	Low Burden	Low Burden	Low Burden	Low Burden
	RI	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE
LBCJMA	HA	Low Burden	Low Burden	Low Burden	Low Burden	Low Burden	Low Burden	Low Burden	Low Burden
	RI	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW
Morrisville	HA	Low Burden	Low Burden	Low Burden	Low Burden	Low Burden	Low Burden	Low Burden	Low Burden
	RI	LOW	LOW	LOW	LOW	LOW	MID-RANGE	LOW	LOW
PWD	HA	Moderate-High Burden	Moderate-High Burden	Moderate-High Burden	Moderate-High Burden	High Burden	Moderate-High Burden	Moderate-High Burden	Moderate-High Burden
	RI	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE	HIGH	MID-RANGE	MID-RANGE	MID-RANGE
Willingboro WPCF	HA	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden
	RI	LOW	LOW	LOW	LOW	LOW	MID-RANGE	LOW	LOW
Wilmington	HA	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden	Moderate-Low Burden
	RI	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE	MID-RANGE

5. Restoration Scenario

The Commission used inflection scenario AA08 as the basis to evaluate a pathway to restoring DO. This scenario represents a technically attainable improvement in DO within the FMA from point source wastewater discharges. Scenario AA08 assigns a constant summer ammonia concentration for the seven Class A’ discharges at 1.5 mg/L and for the two Class A discharges at 5 mg/L; nitrate and CBOD were adjusted accordingly (Section 2.5). In addition, the summer effluent DO for the nine Class A’ and A discharges was assigned the higher of 2 mg/L or the current effluent DO limit (DELCORA and GCUA have current DO limits of 4 mg/L). However, additional factors beyond wastewater reductions were incorporated into the restoration scenario.

5.1 Additional Factors

Four additional factors were considered in a restoration scenario under design conditions: 1) planned CSO reductions; 2) improved effluent DO; 3) seasonally variable wastewater ammonia concentrations; and 4) reserve capacity for future growth. Each is explained below and incorporated into scenario AA15, presented in Section 5.2. The selection of these four factors does not preclude the possibility that other factors not considered here could also impact DO levels in a future restoration scenario.

5.1.1 CSO Reductions

Four utilities operated combined sewer systems in the Delaware River Estuary: PWD, Camden County MUA, DELCORA, and City of Wilmington. Each utility is at various stages of implementation of their long-term control plans (LTCPs) for CSOs. Based on evaluation of each LTCP, the progress “to date,” CSO control results already incorporated into the modeled scenario (for example, the City of Wilmington LTCP is effectively complete and as such the assumed reduction for the restoration scenario is 0%), and conversations with each utility, pollutant loads from CSOs in the restoration scenario were reduced by the percentages shown in Table 5-1.

Table 5-1: CSO reductions assumed for restoration scenario

Combined Sewer System	Post-LTCP % reduction
Philadelphia Water Department	55%
Camden County MUA	59%
DELCORA	51%
City of Wilmington	0%

This CSO adjustment is intended to capture load reductions that can reasonably be expected based on the full implementation of LTCPs, which will be implemented regardless of the outcome of any measures undertaken to improve DO conditions. These reductions are not intended to reflect any additional load reduction requirements, but rather to capture load reductions expected to occur with management programs already in place. The impact of the implementation of CSO LTCPs on scenario AA08 is shown in Figure 5-1.

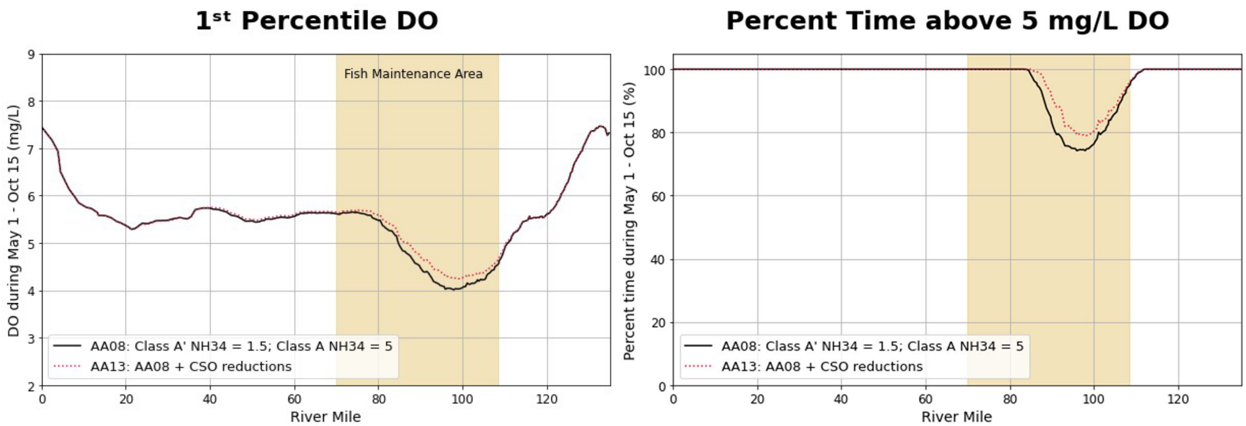


Figure 5-1: Impact of CSO reductions on inflection-scenario DO

5.1.2 Effluent DO Concentration

Removing ammonia via nitrification uses oxygen and, apart from any other design constraints, 2 mg/L would be the expected minimum residual DO after nitrification. Thus, the AA scenarios assigned DO in each effluent discharge with reduced ammonia to 2 mg/L or the current effluent DO limit, whichever is higher. However, effluent DO concentration is important during low DO periods in the FMA and, therefore, must be considered in evaluating a restoration scenario. Figure 5-2 shows the impact of setting effluent DO concentrations from the largest six discharges to a level of 5.0 mg/L. DRBC subsequently tested which discharges can meaningfully impact DO in the FMA and at what effluent DO levels. In addition, DRBC amended the cost and feasibility study to further evaluate scenarios that include minimum effluent DO levels. For the purpose of developing this restoration scenario, summer effluent DO was set to a level of 4 mg/L for all nine Class A' and Class A discharges.

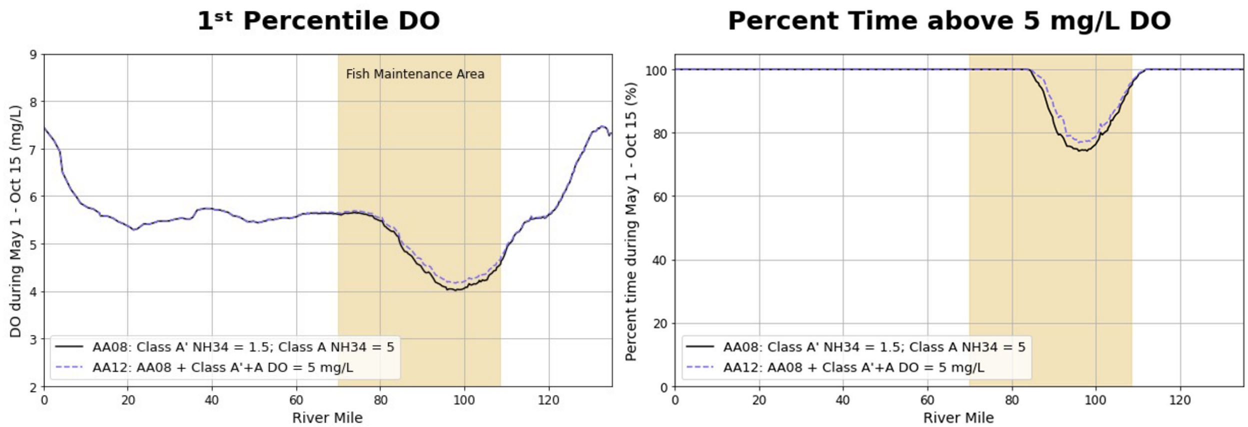


Figure 5-2: Impact of effluent DO on inflection-scenario DO

5.1.3 Seasonally Variable Wastewater Concentrations

Recall that wastewater load reduction scenarios were developed by assigning constant summer effluent concentrations that correspond to particular reduction profiles. For instance, a scenario to simulate reducing ammonia to a level of 1.5 mg/L for a particular discharge would involve assigning a constant ammonia concentration to that discharge during the "summer" (May 1–October 31). This is an extremely conservative methodology. First, a treatment plant required to meet a level of 1.5 mg/L during the entire summer, regardless of exactly how that level were implemented in a wastewater permit (e.g., as a daily, weekly, or monthly average), would be designed to always be below 1.5 mg/L. Simulating the concentration as a constant value equivalent to the target level is therefore very conservative. Second, the treatment design for the plant would be based on the months of May and October, when temperatures are lowest. Nitrification is a highly temperature-dependent process; therefore a plant meeting a level of 1.5 mg/L in May and October will perform better during warmer months. Finally, even if the nitrification process were not operating year-round, any plant designed to hit an effluent limit in May would begin the process no later than April to ensure performance by May 1. To better capture a restoration scenario, a slightly more realistic assignment of wastewater concentrations was utilized based on Table 5-2. This methodology has been compared to actual data from plants in New Jersey and remains very conservative compared to actual effluent concentrations. Applying this methodology is not intended to suggest any changes to wasteload allocations or intra-seasonal effluent limitations; instead it is intended to better capture implementation of summer ammonia limits.

Table 5-2: Wastewater adjustments assumed for restoration scenario

Months	Adjustment	Simulated ammonia (mg/L)	
		SV = 1.5	SV = 5
April	1.5 × SV	2.25	7.5
May, October	1 × SV	1.5	5
June, September	5/6 × SV	1.25	4.17
July, August	2/3 × SV	1	3.33

Note: SV = scenario value

5.1.4 Reserve Capacity

Reserve capacity is based upon an assumption that additional ammonia load that could be held in reserve by DRBC for the consideration of future growth. This load may be allocated to new or expanding discharges by Zone or at the discretion of the Commission. For the purpose of preparing a restoration scenario that reflects a reasonable level of assumed reserve capacity, the ammonia concentration assigned to all modeled dischargers was increased by 10%.

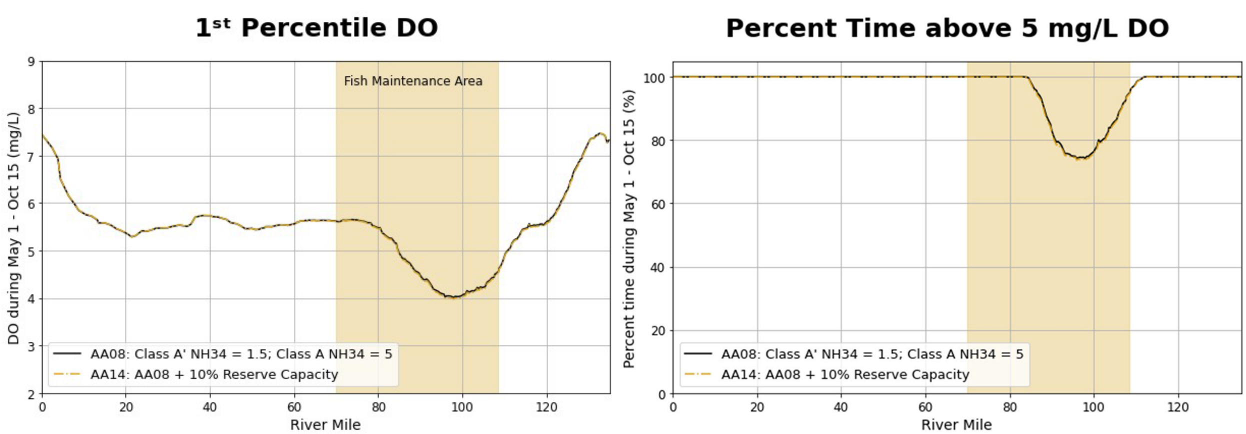


Figure 5-3: Impact of 10% reserve capacity on inflection-scenario DO

A total of 67 wastewater discharges were considered in the eutrophication model and restoration analysis. To accommodate future growth, an additional 10 percent of ammonia load from all discharges was calculated based on the inflection scenario AA08. Using this approach, a total of 709 kg/day ammonia load (equivalent to 125 MGD at 1.5 mg/L) was incorporated. As shown in Figure 5-3, a 10% reserve capacity using this methodology does not substantially change DO conditions.

5.2 Estimated Restoration Scenario DO

Scenario AA15 incorporates all the modifications to inflection scenario AA08 described in Section 5.1, and was developed to estimate one possible restoration scenario if the effluent reductions specified in the inflection scenario (AA08) were implemented. As shown in the comparison among baseline (AA01), AA08, and AA15 scenarios (Figure 5-4), under design conditions the restoration scenario would increase the trough of the DO sag by 2.3 mg/L and shift the trough upstream by 10 miles, from RM 90 to RM 100. This shift would move the DO sag farther away from a known breeding area for the endangered Atlantic Sturgeon.

Figure 5-5 shows the longitudinal 1st, 10th, 25th, and 50th (median) percentile predictions for the baseline (AA01) and restoration (AA15) scenarios, as well as the differences in minimum percentile values within the FMA. This visualization provides a more complete picture across the lower end of the frequency distribution and illustrates the significant improvement in DO conditions that could be expected from implementation of the wastewater effluent reductions specified in the inflection scenario.

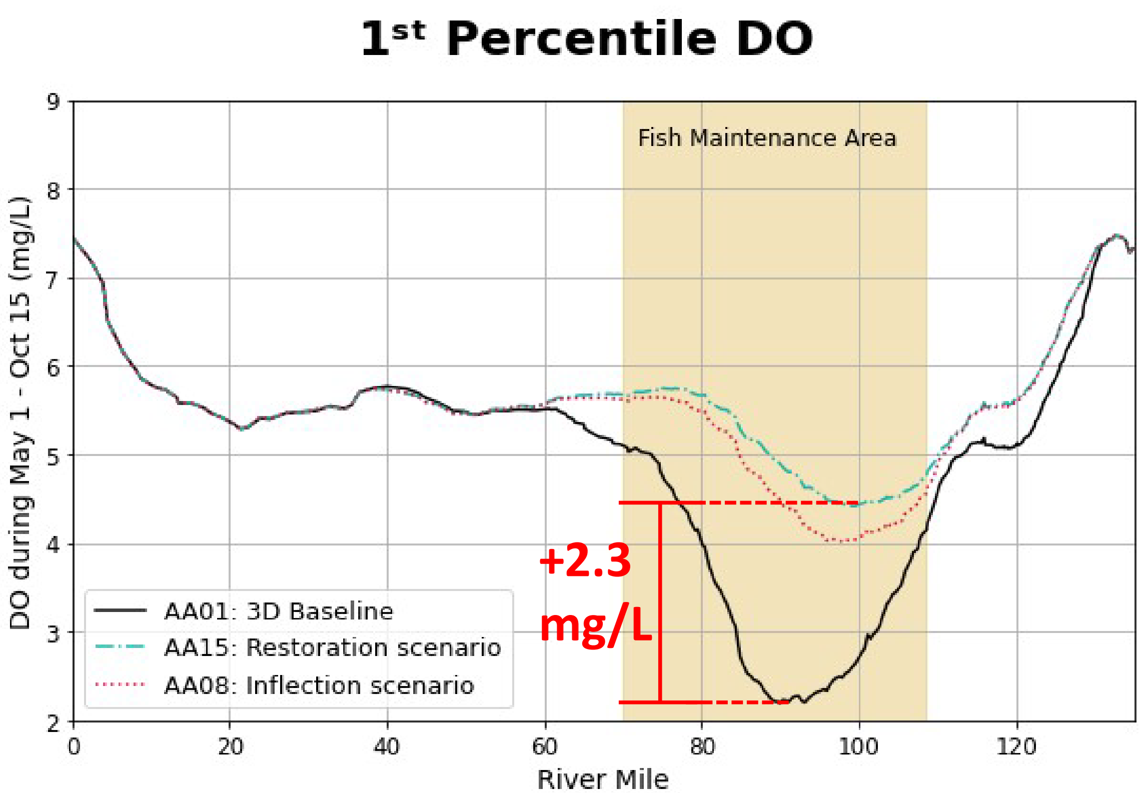
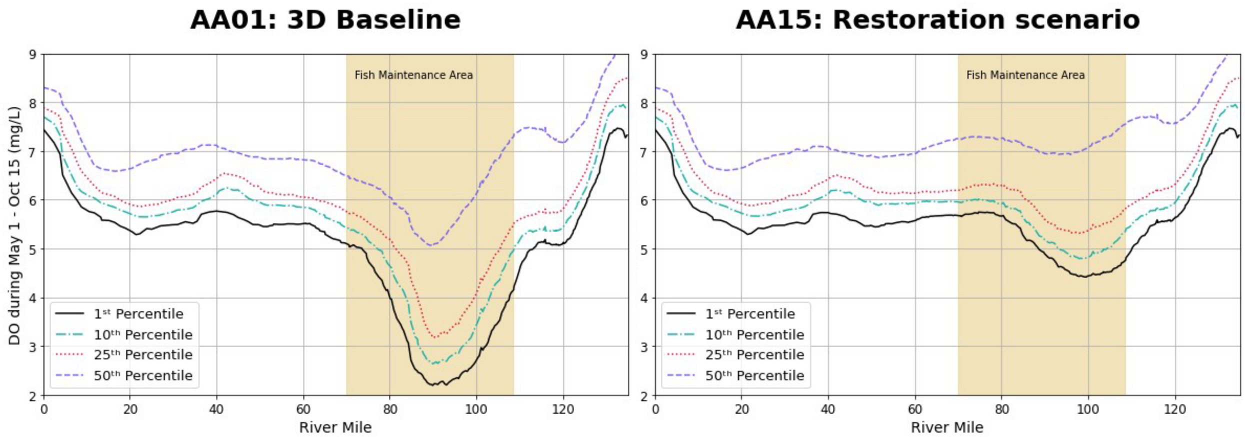


Figure 5-4: Comparison of 3D-baseline, inflection-scenario, and restoration-scenario DO



Percentile	Min value in FMA	
	AA01	AA15
1	2.2 mg/L	4.5 mg/L
10	2.6 mg/L	4.8 mg/L
25	3.2 mg/L	5.4 mg/L
50	5.0 mg/L	7.0 mg/L

Figure 5-5: Predicted DO percentiles for 3D baseline and restoration scenarios

Figure 5-6 visually displays improvement to 1st percentile DO throughout the FMA portion of the Estuary. The left maps show 1st percentile DO expected under the restoration scenario and the right maps show increases in 1st percentile DO relative to the baseline scenario (AA01), zooming in on RM 85–94, where the current DO sag is centered. Increases to the lowest-DO values are consistent throughout the current DO sag, representing 2.4–2.8 mg/L of DO improvement at every modelled location within RM 85–94. Similarly, Figure 5-7 shows the profound difference and significant improvement in DO Relative Stress Index, a metric that captures the relative differences in potential DO stress to fish, within the FMA for the baseline and restoration scenarios. The tabular results in Figure 5-6 also demonstrate the consistency of the results within each transect (i.e., from bank to bank); this demonstrates that the longitudinal spatial plots used throughout this report are representative.

Finally, Figure 5-8 shows the 1st percentile DO predicted for the restoration scenario under actual wastewater flow (as opposed to permitted) and hydrology conditions in 2012, 2018 and 2019, compared with restoration-scenario DO under design conditions. As described in Section 2.3.1, the years 2012, 2018, and 2019 incorporate a range of temperatures and flows that can be generally characterized as more critical, less critical, and more typical, respectively. Additional comparisons between baseline and restoration scenarios (including longitudinal plots for 1st, 10th, 25th and 50th percentiles, longitudinal plots for percent time over 4, 5, 6 and 7 mg/L, and tabular maps for 1st percentile DO), as well as comparisons of the restoration-scenario DO under different flow conditions, are provided in Appendix C.

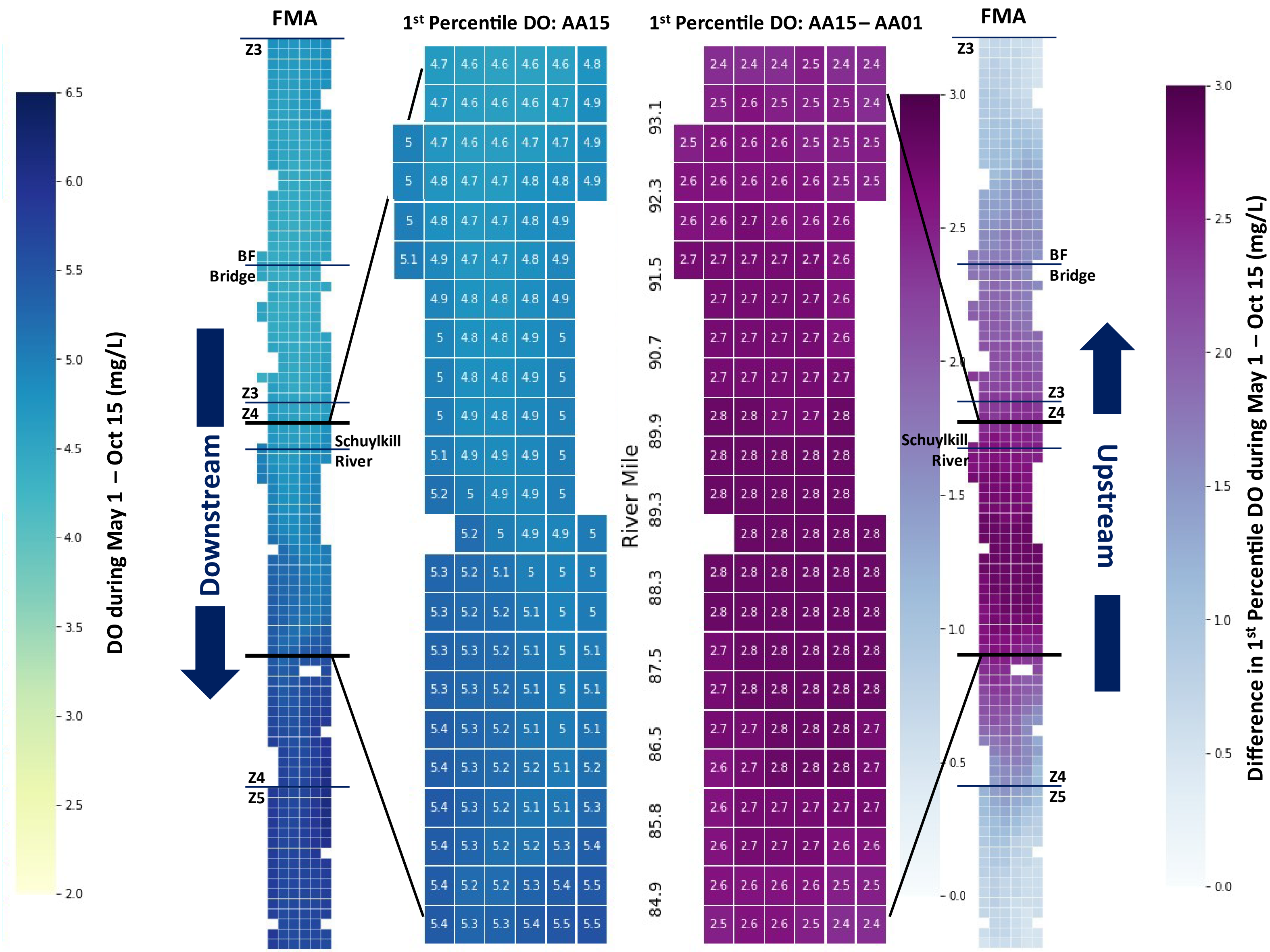


Figure 5-6: Tabular maps of DO improvement in FMA under restoration scenario

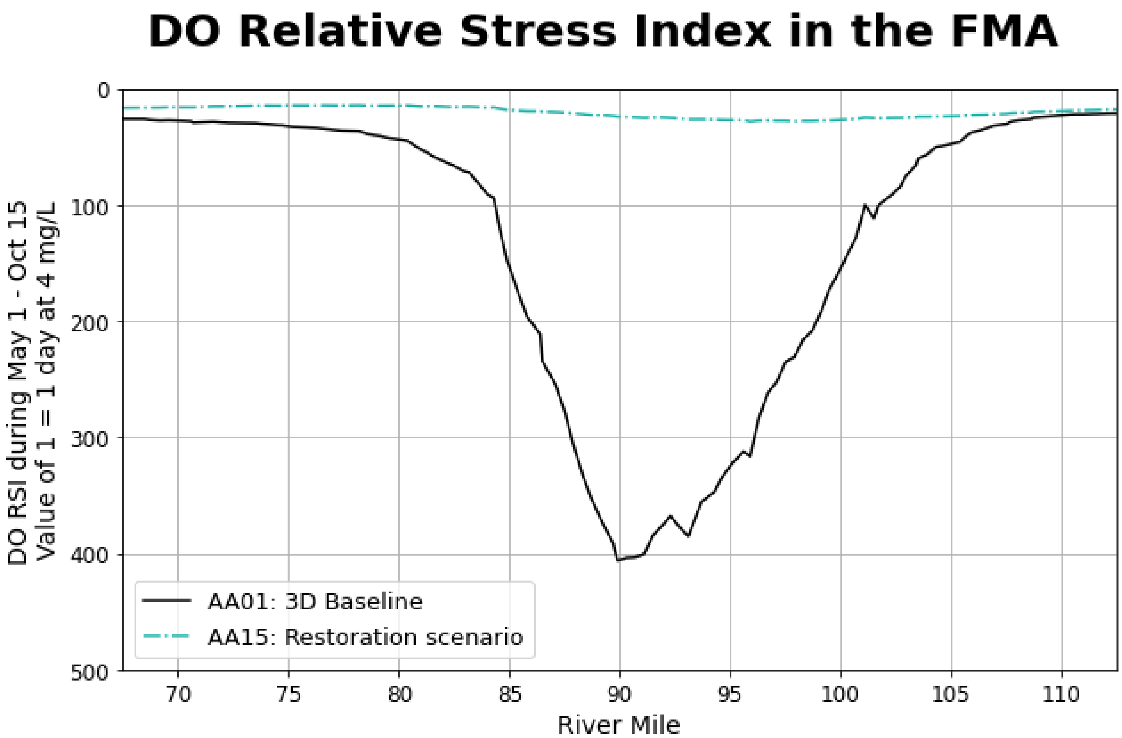


Figure 5-7: Expected improvement in DO RSI in restoration scenario

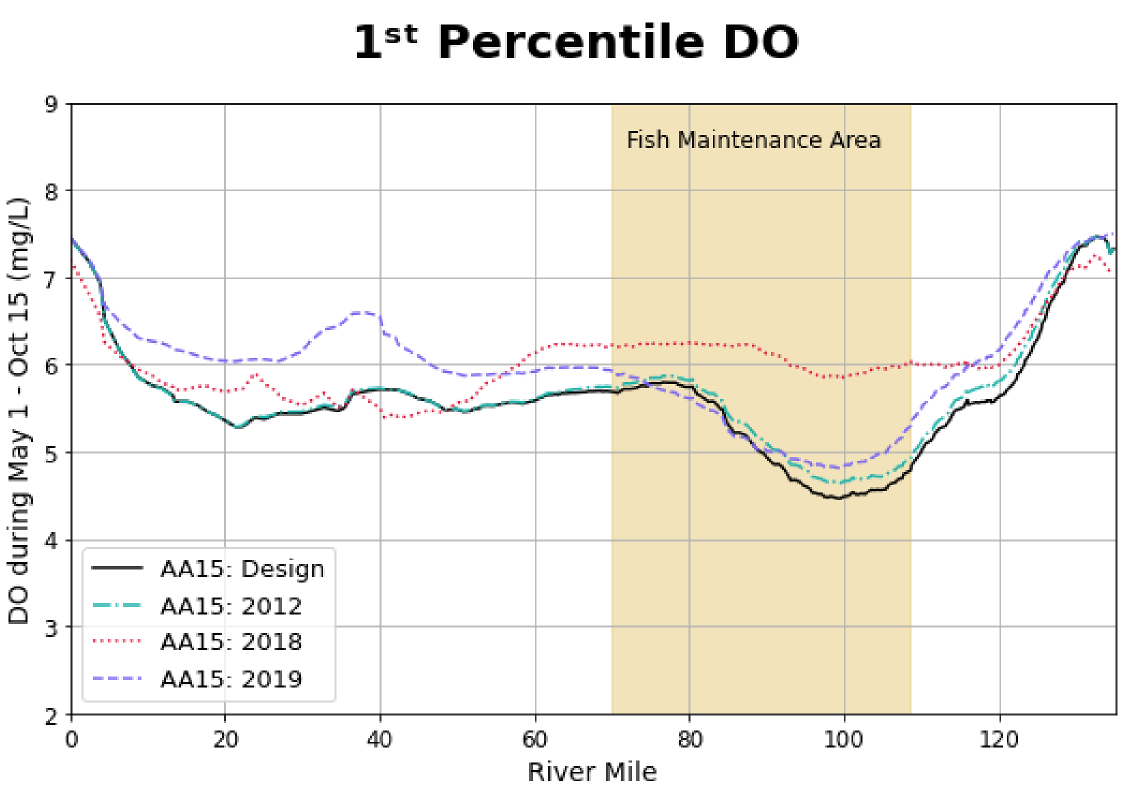


Figure 5-8: Restoration-scenario DO under different flow conditions

AA15 represents a possible restoration scenario under critical conditions based on the physics, chemistry and biology of the system. As demonstrated above, the minimum DO under critical design conditions would increase from 2.2 to 4.5 mg/L in the FMA, and this would be accompanied by a significant increase in the duration during which the DO will be over 4, 5, 6, and 7 mg/L at any location. Under design conditions, DO in the restoration scenario would be greater than 5 mg/L 100% of the time during nine months of the year, and the minimum percent of time spent above 5 mg/L during the months of July through September would increase from 17% to 68% compared to the baseline scenario, as shown in Figure 5-9. Furthermore, the number of river miles over which the water column under critical conditions can be expected to ever drop below 5 mg/L will decrease from 51 to 12 miles. These changes would represent a substantial improvement in DO conditions for the Estuary.

In addition to restoration scenario AA15, the DRBC prepared additional water quality simulations specifically for EPA's use in its rulemaking to revise the aquatic life use and supporting water quality criteria for DO in the FMA (Appendix D). These simulations incorporate minor adjustments to the baseline design condition and restoration scenario AA15.

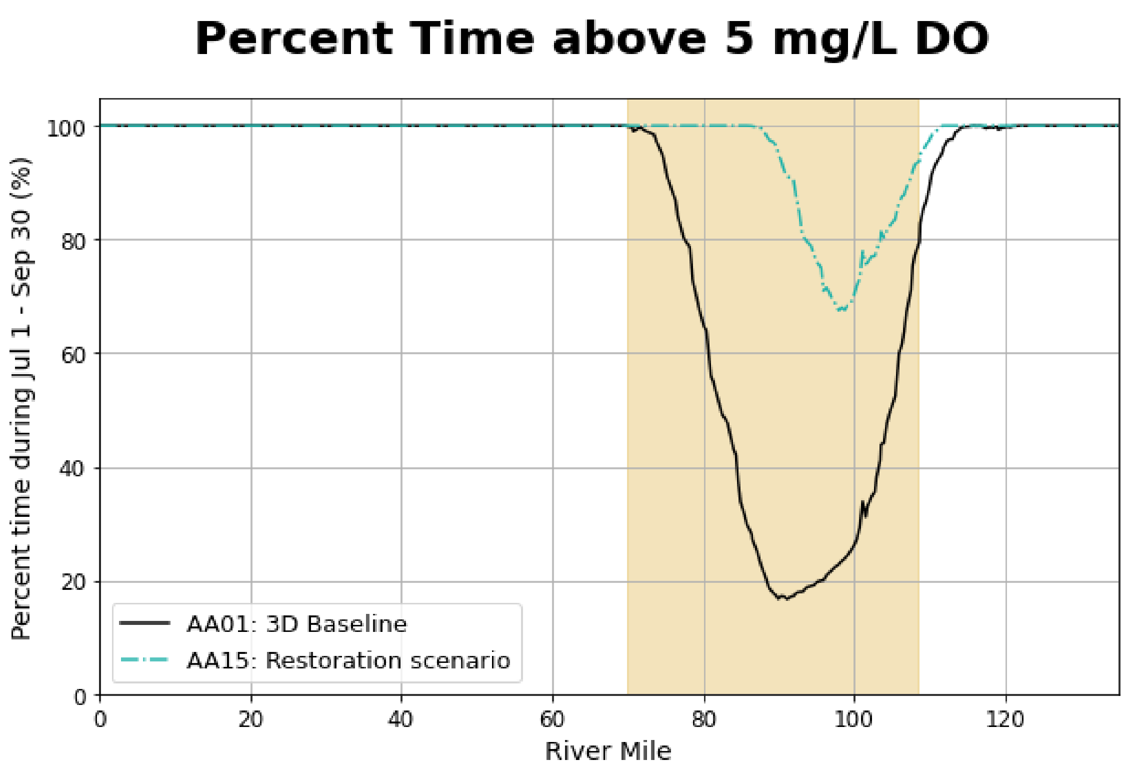


Figure 5-9: Percent of time above 5 mg/L (July–September) for 3D baseline AA01 and restoration scenario AA15.

6. Technical Summary

DRBC staff completed a series of studies to assess the potential for improved dissolved oxygen conditions in the FMA. DRBC staff developed and calibrated a linked, three-dimensional hydrodynamic and eutrophication model for the Delaware River Estuary, and then applied the model to evaluate potential pathways to DO improvement via nutrient control scenarios. The staff performed multiple sensitivity and test scenario simulations to identify key variables and sources that have the potential to improve the DO sag around Philadelphia, Pennsylvania, and Camden, New Jersey, and to enhance overall DO conditions in the FMA.

The Commission's directives, including Resolution 2017-4, emphasized the importance of a collaborative process informed by technical studies and specialized scientific and engineering expertise. From the outset of this project, DRBC staff have drawn on the expertise of the Commission's member agencies and the basin community through the WQAC, meetings with co-regulators, and consultation with its Model Expert Panel. The Commission's WQAC is comprised of representatives from DRBC's state and federal partner agencies, the industrial and municipal regulated community, environmental groups, local watershed organizations, and academia. Its meetings are announced in advance and open to the public. Since the adoption of Resolution No. 2017-4, the WQAC has met twenty-three times, including monthly from April through September 2022, to share and discuss the baseline design conditions, assumptions, scenario development, evaluation metrics, findings, and overall progress of the studies. Staff engaged in an even greater level of interaction with the Model Expert Panel, meeting as frequently as every three weeks during critical phases of the project. As necessary, staff met with dischargers individually to gather more reliable information and to improve assumptions used in the studies. The results presented in this report are summarized below.

<u>Summary of Restoration Analysis</u>

A restoration analysis was performed under 2012 hydrologic conditions, which exhibited the worst ambient DO conditions observed in the Estuary in more than 12 years. The baseline design condition was developed utilizing the permitted effluent flows for sixty-seven (67) wastewater discharges. Effluent concentrations were assigned using median values derived from 2018–2019 effluent monitoring data to reflect current effluent characteristics. The work comprising this analysis, together with supporting studies, including those performed by the DRBC and those it commissioned, shows:

- The addition of technically feasible advanced treatment by nine (9) out of 67 wastewater point-source discharges to reduce effluent ammonia nitrogen during the summer season (May to October) has the potential to significantly improve the level of dissolved oxygen that can be achieved in the FMA (Zones 3 and 4 and upper portion of Zone 5). These nine discharges contribute 96 percent of total ammonia nitrogen load from wastewater treatment point-source discharges to the Delaware River Estuary. The range of applied effluent ammonia nitrogen reduction from these nine point-source dischargers (for inflection scenario AA08) is 61–94% from assigned effluent loading conditions, with an overall reduction of 87%. The reduction percentages show a wide range due to varying initial ammonia nitrogen concentrations.

Under selected scenario AA08:

- Seven (7) wastewater treatment plants located in the FMA—Northeast Water Pollution Control Plant (PWD NE), Southeast Water Pollution Control Plant (PWD SE), Southwest Water Pollution Control Plant (PWD SW), Camden County Municipal Utilities Authority (CCMUA), Gloucester Utility Authority (GCUA), Delaware County Regional Water Quality Control Authority (DELCORA), and City of Wilmington Wastewater Treatment Plant—reduce effluent ammonia nitrogen concentration to a level of 1.5 mg/L in order to improve DO conditions in the FMA.
- Two (2) wastewater treatment plants located in Zone 2—Hamilton Township Water Pollution Control Facility and Lower Bucks County Joint Municipal Authority (Lower Bucks Joint MA)—reduce effluent ammonia nitrogen concentration to a level of 5 mg/L to improve DO conditions in the upper portion of the FMA.

- Feasibility and costs to achieve various effluent pollutant concentration levels were characterized based on proven treatment technologies with long-term performance records to ensure a reasonable degree of confidence in plant upgrade performance for each of the existing treatment types (DRBC, 2021).
    - Estimated annualized present cost for recommended wastewater improvements for AA08 is approximately $153M per year in 2019 dollars, which includes annualized present worth cost and annual operation and maintenance cost. The complexity degree of cost estimate is American Association of Cost Estimating (AACE) Level 4 estimate.
    - Total Present Worth Cost is $2.6B in 2019 dollars.
    - The capital, operations, and maintenance costs of advanced treatment associated with scenario AA08 are significant; however, based upon analyses performed using EPA and utility industry (AWWA, NACWA, and WEF) methods, the cost burden of the additional treatment will not increase the affordability burden category on a utility service area scale for the affected treatment plants based on current costs. Future obligations could also contribute to ratepayer cost increases, which could change the impact that scenario AA08 costs would have on burden categories.
- A restoration scenario (AA15) was developed based on inflection scenario AA08. Four additional measures were considered which would impact the ambient DO conditions:
    - Full implementation of CSO long-term control plans (LTCPs);
    - Effluent DO of 4 mg/L for all nine dischargers;

  - Lower than 1.5 mg/L summertime effluent ammonia nitrogen conditions for the nine point-source dischargers, due to expected higher treatment efficiency during warmer temperatures; and
  - Addition of a ten (10) percent ammonia load to sixty-seven point-source dischargers as a reserve capacity.
- The restoration scenario (AA15) simulation predicts profound improvements in the DO condition within the FMA.
  - At 1st percentile "critical" conditions, the minimum DO at the lowest point of the sag would increase by approximately 2.3 mg/L to approximately 4.5 mg/L.
  - The lowest point of the DO sag would move upstream approximately 10 miles to around RM 100, farther away from a known breeding area for the endangered Atlantic Sturgeon.
  - DO would be greater than 4.5 mg/L 100% of the time throughout the FMA. DO is currently greater than 4.5 mg/L only about 50% of the time within the DO sag.
  - DO would be greater than 5.0 mg/L throughout the FMA at least 83% of the time.
  - DO would be greater than 6.0 mg/L throughout the FMA at least 62% of the time.
  - DO would be greater than 7 mg/L throughout the FMA at least 50% of the time.
- A semi-empirical methodology to improve modeled estimates of DO at ungaged locations was developed and used to evaluate restored DO potential across a 15-year period (Appendix A).

While this study identifies the pollutant sources impacting dissolved oxygen in the urban portion of the Estuary as well as the magnitude of improvement that can be expected after reduction of those pollutant sources, the study does not provide a basis for valid wasteload allocations. Rather, it is a comparative study based on discrete scenarios and makes no attempt to iterate the exact allocations that would result in attainment of a particular water quality end point. When revised DO criteria are promulgated for the Delaware River Estuary, DRBC anticipates working with the Estuary states and the EPA to conduct a wasteload allocation study that could provide the basis for the states to impose effluent limits on dischargers to satisfy the new criteria.

Finally, at the request of the EPA, the DRBC prepared four additional water quality simulations that incorporate minor adjustments to the baseline (AA01) and restoration (AA15) scenarios. These scenarios, described in Appendix D, were prepared specifically for EPA's use in its rulemaking to revise the aquatic life use and supporting water quality criteria for DO in the FMA.

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Appendix A: Improving Estimation of Modeled Dissolved Oxygen Conditions with Observed Data

**The methodology described herein was developed by DRBC staff Thomas Amidon, Sarah Beganskas, and Jake Bransky in consultation with DRBC's Model Expert Panel.*

INTRODUCTION

The goal of this analysis is to leverage the strengths of the EFDC–WASP model alongside many years of observed DO data to improve estimation of DO at unmonitored locations across different loading scenarios beyond what is possible with model output alone. The EFDC–WASP model generated DO predictions under baseline (AA01) and restored (AA15) scenarios based on hydrologic conditions for three years: 2012, 2018, and 2019. The year 2012 was selected as the basis for the baseline and restoration scenarios presented in this report, though this year may represent a relatively infrequent occurrence of low-DO conditions. As discussed in Section 2.6, modeled DO predictions necessarily contain some degree of uncertainty (Zheng et al., 2024). Gage data provide additional information that can be used to inform and improve model predictions in a way that does not propagate all model uncertainty. Thus, results from this semi-empirical method have less uncertainty than model predictions alone. This approach was applied to evaluate inter-year variability in restored DO conditions by expanding results to cover 15 years. The methodology could be applied in other ways to reduce uncertainty associated with model predictions at unmonitored locations and under different loading scenarios.

DATA INPUTS

Continuous Dissolved Oxygen Gage Data

Continuous DO data is available at an hourly time step for 15 years (2008–2009 and 2011–2023) at two gage locations in the Delaware River Estuary: Chester, Pennsylvania (USGS 01477050), and Penn's Landing, Pennsylvania (USGS 01467200, formerly known as Ben Franklin Bridge). The Chester gage is located at River Mile (RM) 83.6 in water quality Zone 4 and the Penn's Landing gage is at RM 99.6 in water quality Zone 3.

Dissolved Oxygen Model Predictions

A 2-hour time-series of DO predictions is generated for every cell in a 3D representation of the Estuary. The I-dimension indicates position across the channel width, the J-dimension indicates position up- or downstream, and the K-dimension indicates depth within the water column. Depth-averaged DO at each I,J location was calculated as the mean of DO results at each depth (K-value). Predicted depth-averaged DO time-series for 2012, 2018, and 2019 were used from the baseline (AA01) and restoration (AA15) scenarios.

METHODOLOGY

Change Factor Concept

The approach applied here is similar in concept to the change factor methodology, also known as delta change factor, that has been commonly applied in climate science for many years (e.g., Anandhi et al., 2011; Navarro-Racines et al., 2020). In the context of climate change, "change factors" or "delta change factors" are calculated as the difference between simulated future (*F*) and simulated historic (*H*) conditions at a given time and location. Change factors are commonly applied to both climate data (e.g., temperature or precipitation) and secondary variables that are affected by climate (e.g., streamflow). The change factors may be additive (CF_a) or multiplicative (CF_m) depending on the context:

$$CF_m = \frac{F}{H} \quad \text{or} \quad CF_a = F - H$$

The change factors are then applied to observed historic data by adding (CF_a) or multiplying (CF_m) each value in a historic time series by the corresponding change factor. As a result, the climate models are used to characterize the *relative change* that is expected in a given variable under a future scenario, rather than predicting an absolute value for that variable. This methodology also *preserves characteristics of the observed dataset* that may not be fully captured or reproduced in climate models—for example, local storm tracks or prolonged drought.

Similarly, the approach described here leverages the EFDC-WASP model's strengths in quantifying the *difference* between the baseline scenario and an alternate restoration scenario (Figure A-1). Those differences are applied to observed DO gage data (representing the baseline condition), providing an estimation of what each observed year might have looked like under a restored scenario. An additional benefit is that restored conditions can be evaluated for all 15 years with observed data, rather than being limited to the three years for which model simulations were developed.

The EFDC–WASP model was used in a similar fashion to develop relationships between DO at observed gage locations and all other modeled locations in Zones 3 and 4. Thus, baseline (existing) and restored DO could also be estimated at many ungaged locations throughout the urban Delaware Estuary (Figure A-1).

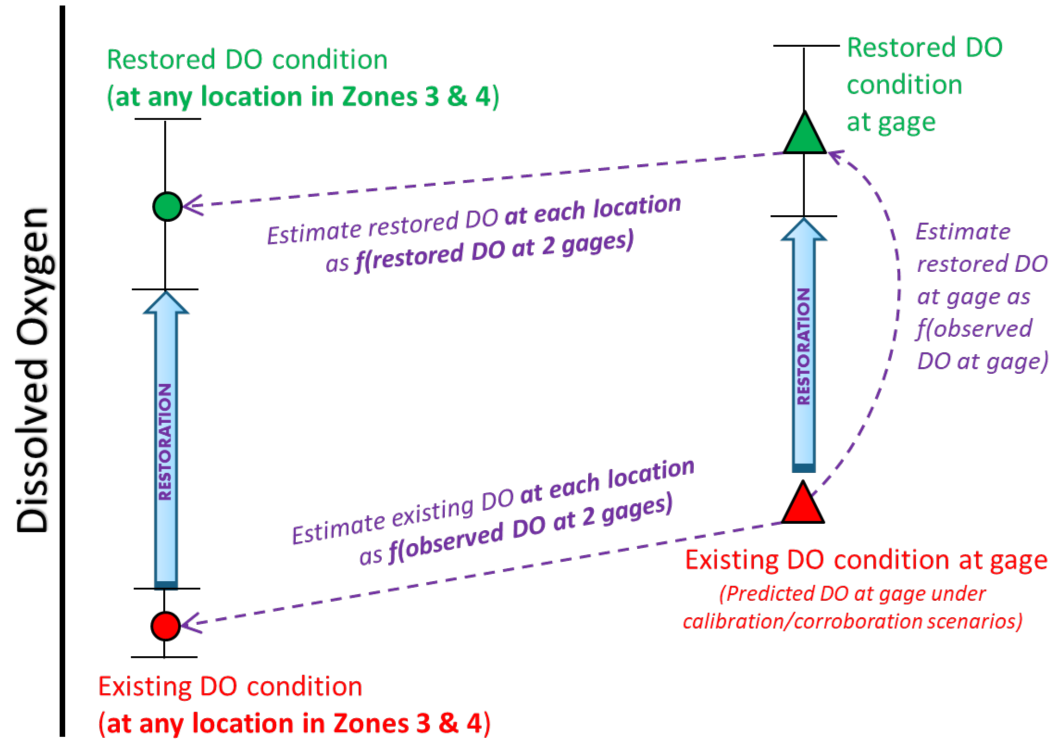

Figure A-1: Conceptual diagram representing how a combination of model and observed data were used to estimate restored DO at both gaged and ungaged locations.

Regressions

Given the complexity of DO dynamics, rather than applying a simple additive or multiplicative change factor, a combination of the two was employed: linear regression. Figure A-2 shows the linear relationships between baseline (calibrated) and restoration-scenario dissolved oxygen at the Chester and Penn's Landing gage locations. These regression plots show model output at 2-hour resolution. The top plots show the regressions that were applied to observed data, combining data from model-years 2012, 2018, and 2019. The bottom plots show that there is not substantial variability in the regression equations across these three years when they are evaluated independently. At each gage, the corresponding regression equation was applied to every DO observation across 15 years, generating an hourly time series of restored DO at each gage.

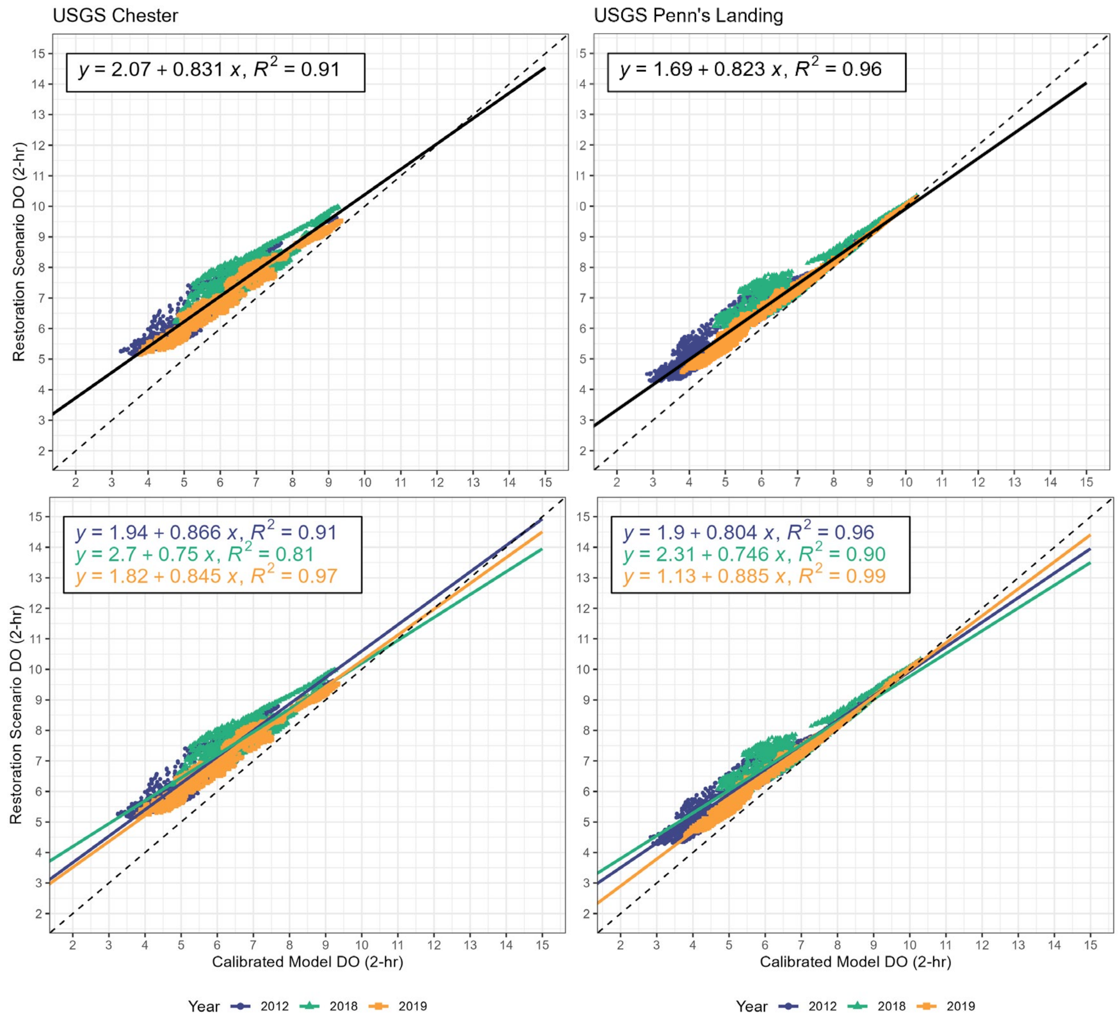

Figure A-2: Regression equations used to define the relationship between baseline and restoration-scenario DO at the Chester (left column) and Penn's Landing (right column) gage locations.

For each un-gaged, modeled location in Zones 3 and 4, a regression was developed relating baseline modeled DO at the Chester gage to baseline modeled DO at that un-gaged location, both on a 2-hourly time scale. When these regressions are applied to hourly observed data at the Chester gage, it allows estimation of "existing" DO at ungaged locations throughout Zone 3 and 4. Similarly, baseline modeled DO at every un-gaged location in Zones 3 and 4 was related to modeled DO at the Penn's Landing gage location. Thus, for every un-gaged location in Zones 3 and 4, there are two independent hourly estimates of existing DO: one based on observations from the Chester gage and one based on observations from the Penn's Landing gage.

In an analogous fashion, two independent estimates of *restored* DO were computed for every ungaged location in Zones 3 and 4, using regressions between restored modeled DO at each ungaged location and restored modeled DO at the two gage locations.

Weighting

For both existing and restored scenarios, the two independent hourly DO estimations based on Chester and Penn's Landing gage data were combined into a single hourly estimation at each location. To ensure spatially continuous DO conditions, a weighting factor was assigned to each location based on distance to the gages. Upstream of the Penn's Landing gage (RM 100.1), the Penn's Landing weighting factor was 1 and the Chester weighting factor was 0, indicating that only the Penn's Landing estimation was used. Similarly, downstream of the Chester gage (RM 83.6), only the Chester estimation was used. In between the Chester and Penn's Landing gages, the weighting factors were linearly scaled between 0 and 1 (Figure A-3).

At every I,J location, the Penn's Landing DO estimations were multiplied by the Penn's Landing weighting factors, the Chester Restored DO estimations were multiplied by the Chester weighting factors, and the two were added together to produce final DO estimations for the existing and restored scenarios. The schematic in Figure A-4 outlines the entire methodology for calculating restored DO.

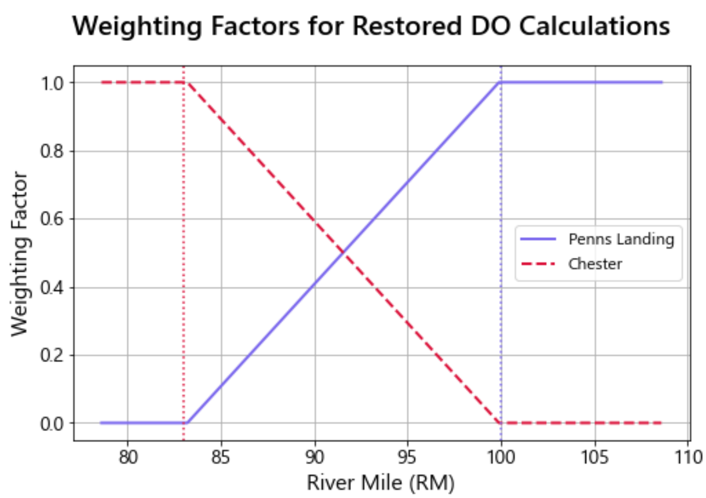

Figure A-3: Weighting factors used to combine Penn's Landing and Chester DO estimations.

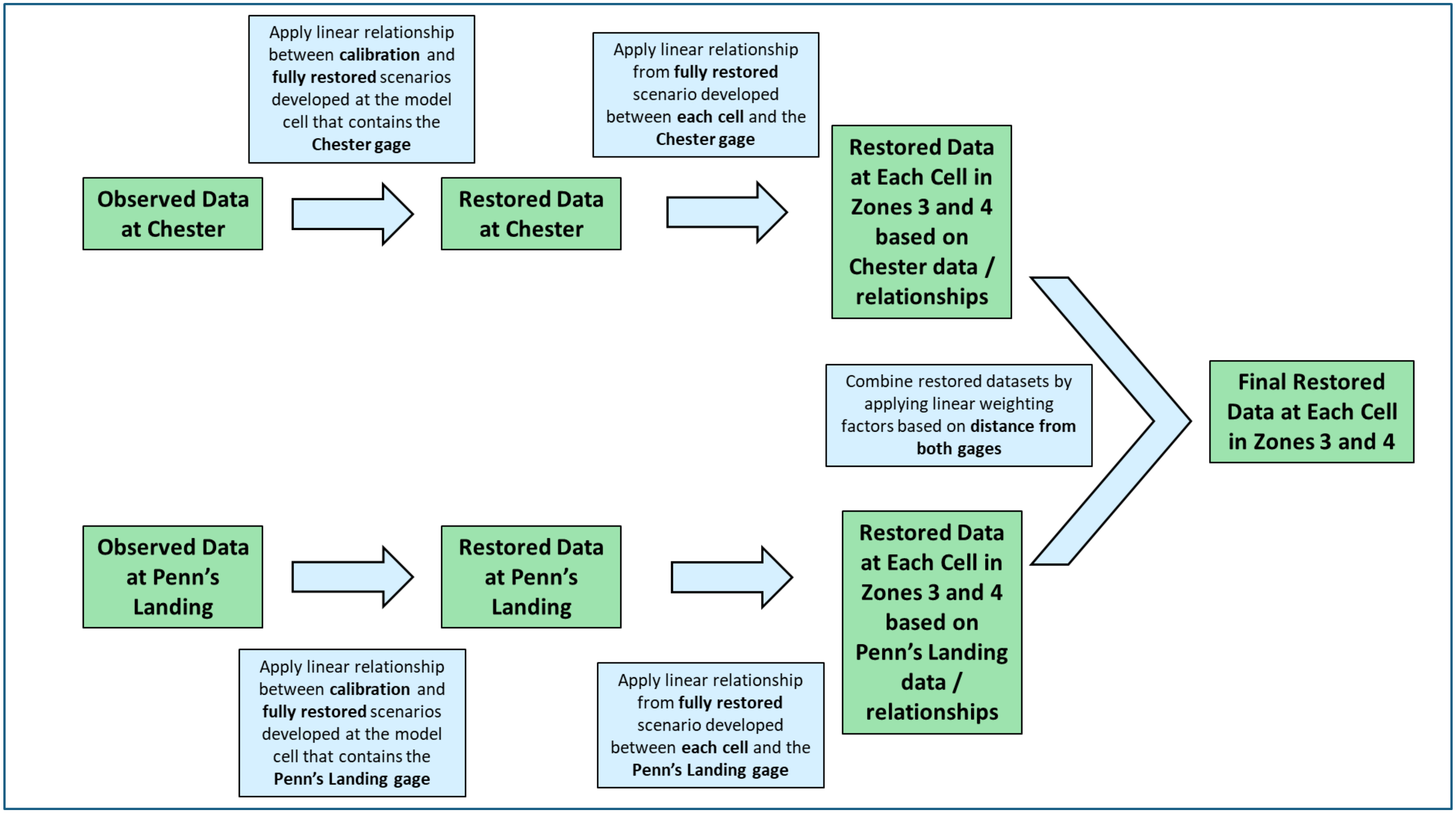

Figure A-4: Schematic of entire methodology for estimating restored DO.

SAMPLE RESULTS: VISUALIZING INTER-ANNUAL VARIABILITY IN RESTORED DO

Figure A-5 shows the distribution of daily-average restored DO values at the Penn's Landing gage for the juvenile fish development (or "growth") season, July 1 through October 31, with each year plotted as a different color. The three years that also have available model output (2012, 2018, and 2019) are shown with thicker lines. The additional 12 years of data provide a richer context for evaluating the frequency with which DO at this location is expected to be greater than any specific value. To guide interpretation, vertical dotted lines are shown at the 10th and 50th percentile.

At each location in the Estuary, distributions like those presented above for the Penn's Landing gage can be calculated. Figure A-6 plots the *minimum* 10th and 50th percentile values among all Estuary locations each year, based on daily-average restored DO estimations. The spread represents inter-year variability.

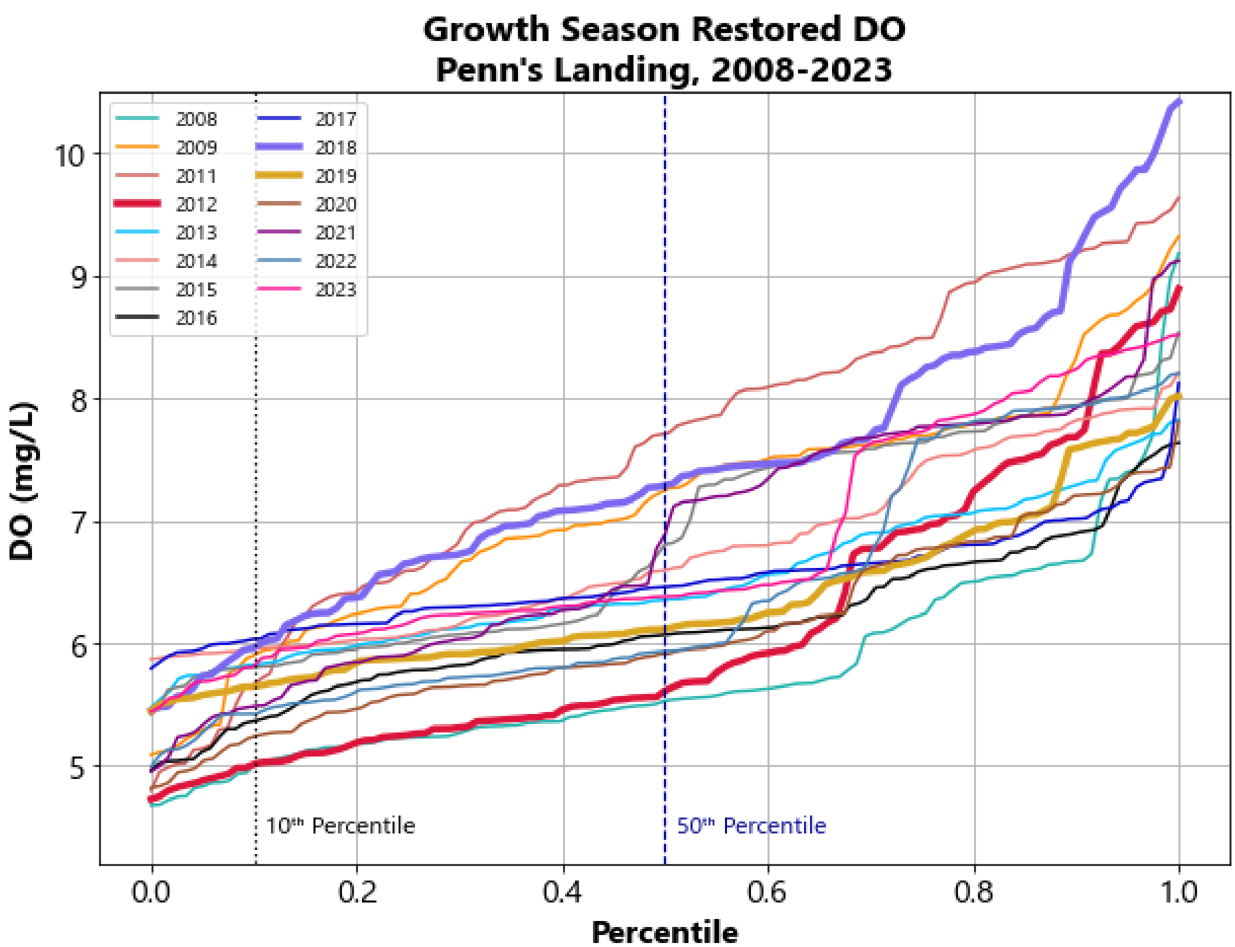

Figure A-5: Estimated restored DO distributions at the Penn's Landing gage for 15 years.

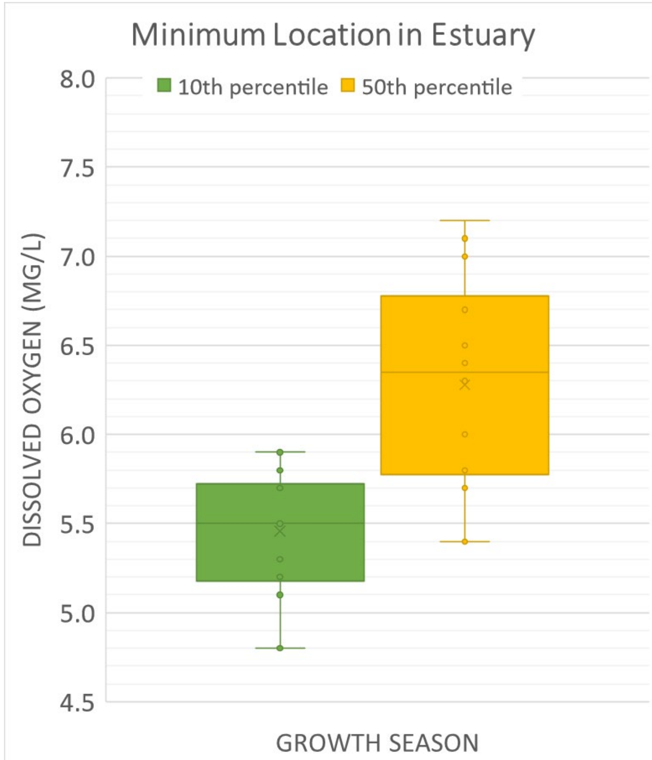

Figure A-6: The distribution of Estuary-minimum 10th and 50th percentile restored DO values over 15 years with observed data.

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Appendix B: AA Scenario Comparisons

- Comparisons among scenarios AA01–AA05
- Comparisons among scenarios AA04, AA06 & AA07
- Comparisons among scenarios AA04, AA07, AA08 & AA10

See Section 4.1 and Table 4-1 for detailed scenario descriptions.

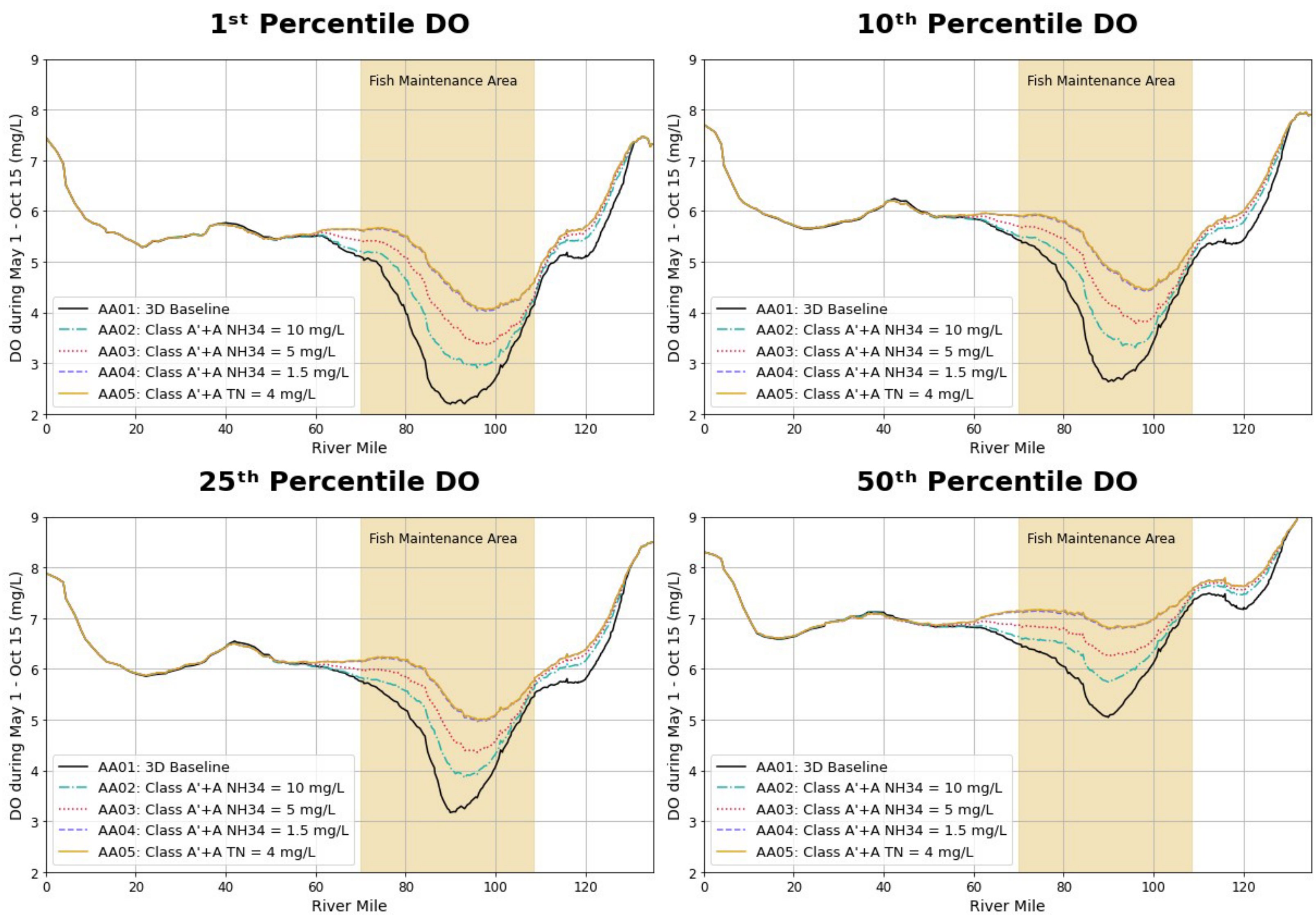

Figure B-1: 1st, 10th, 25th, and 50th percentile results for scenarios AA01–AA05, which represent a range of pollutant reductions for both Classes A' and A.

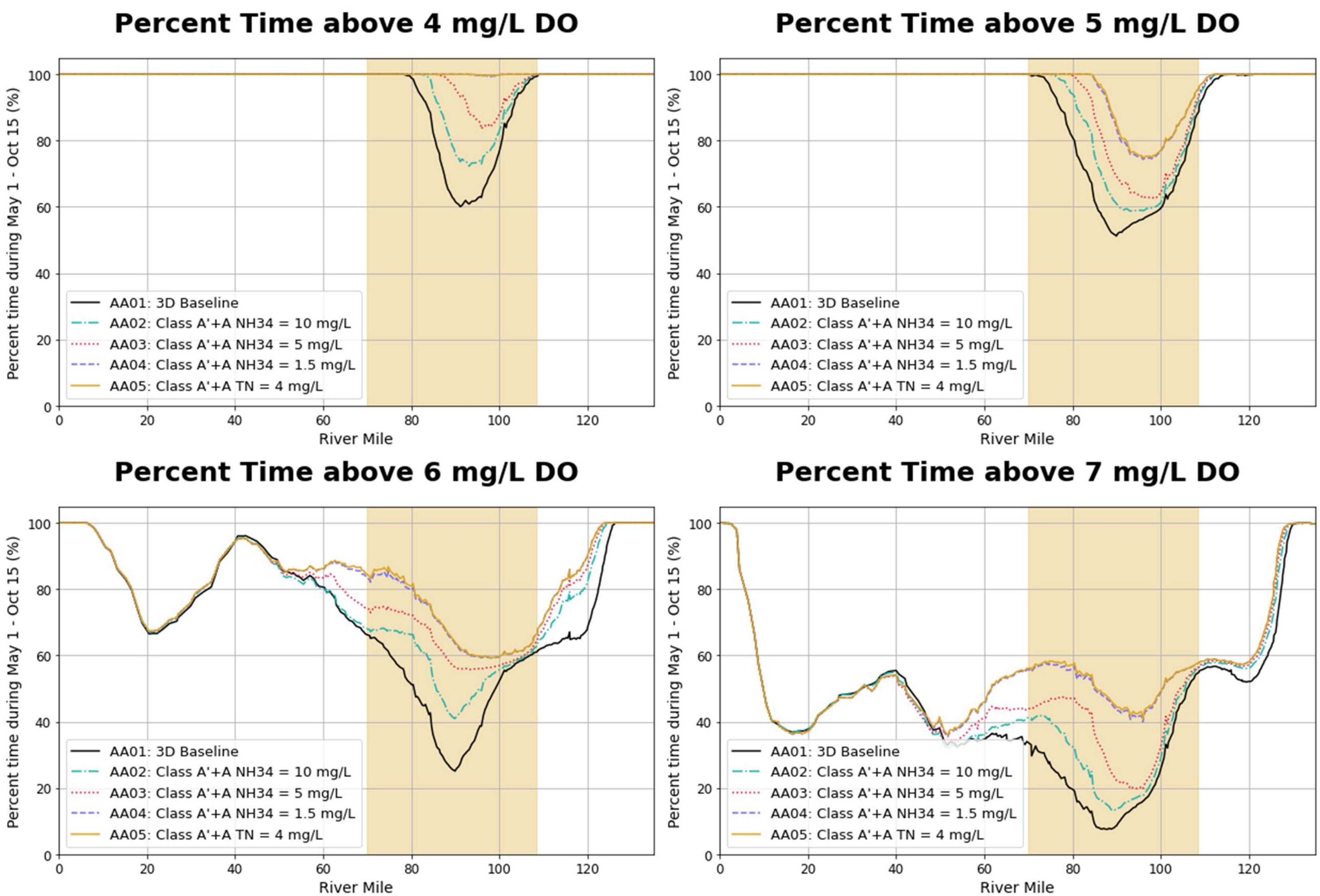

***Figure B-2**: Percent time above 4, 5, 6, and 7 mg/L for scenarios AA01–AA05, which represent a range of pollutant reductions for both Classes A' and A.*

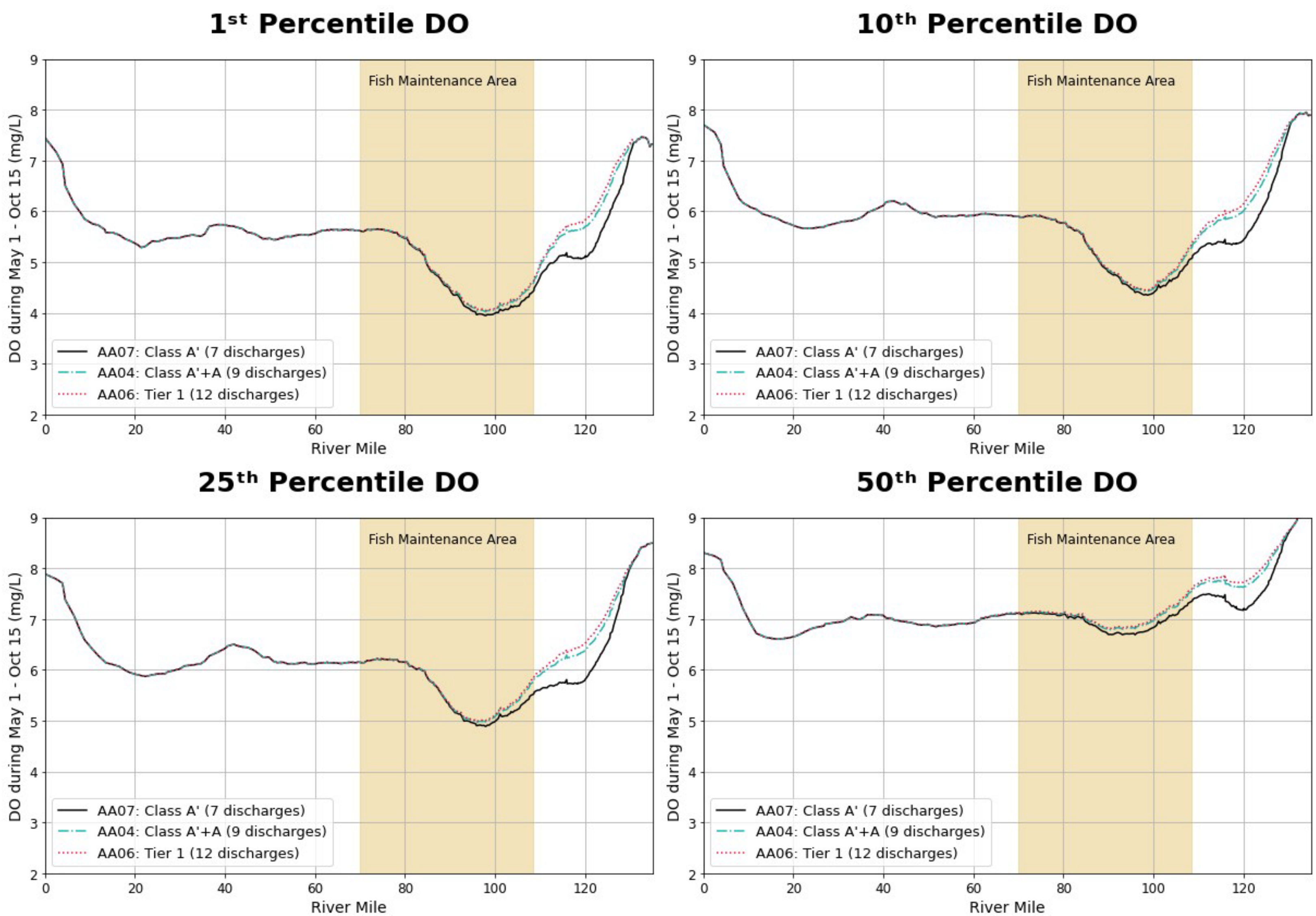

Figure B-3: 1st, 10th, 25th, and 50th percentile results for scenarios AA07, AA04, and AA06, which represent different groups of discharges reducing effluent NH34 to 1.5 mg/L.

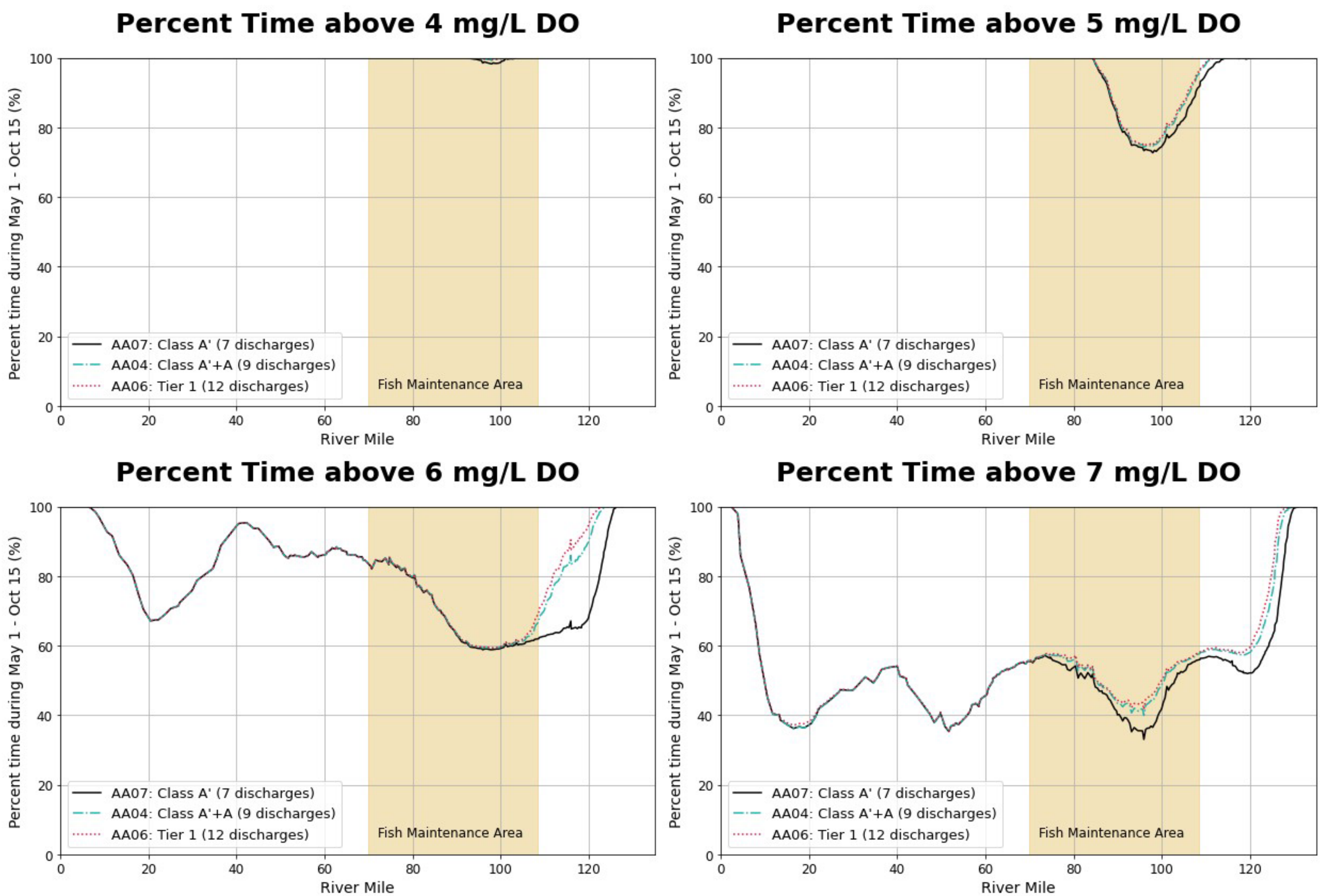

***Figure B-4**: Percent time above 4, 5, 6, and 7 mg/L for scenarios AA07, AA04, and AA06, which represent different groups of discharges reducing effluent NH34 to 1.5 mg/L.*

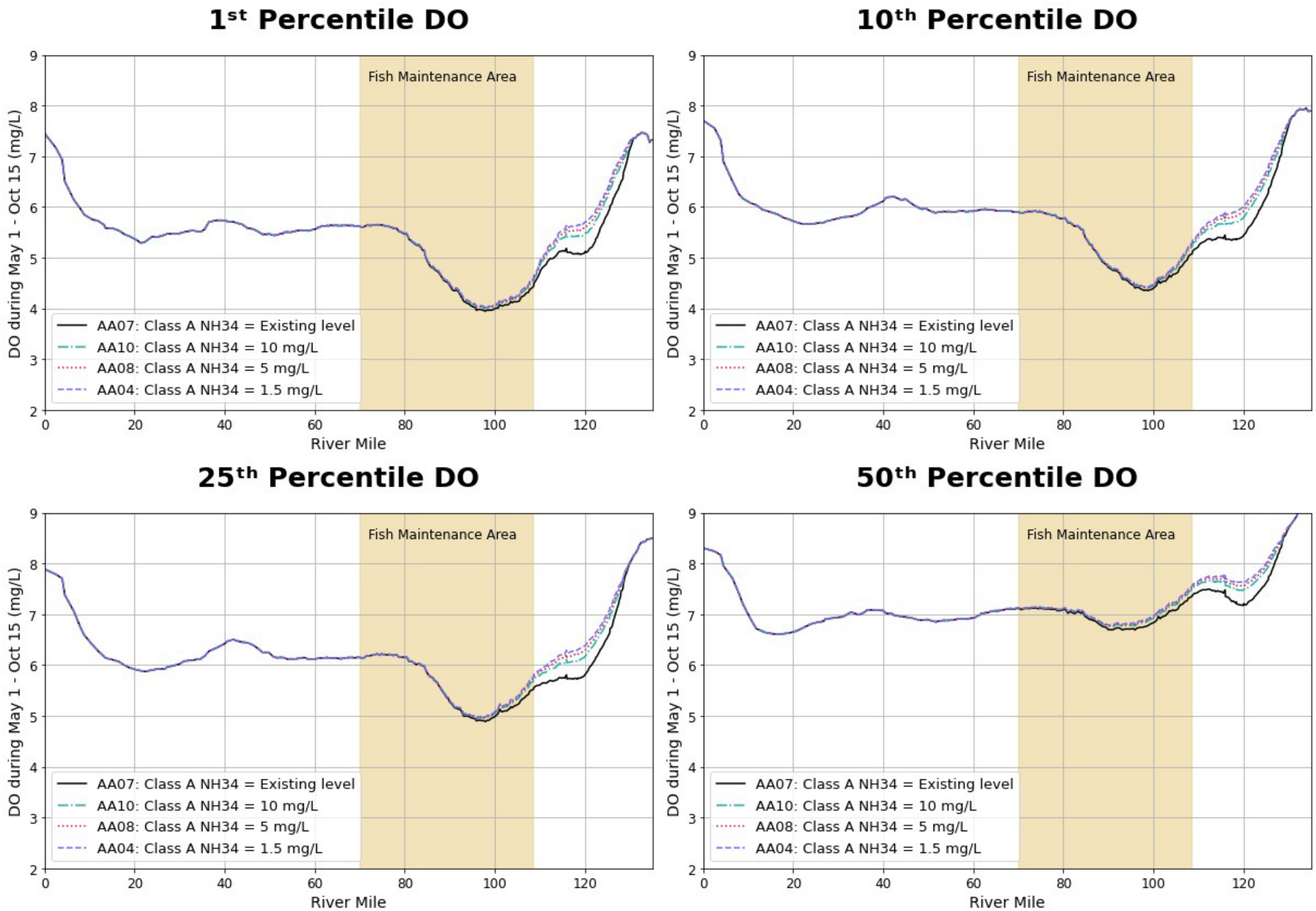

***Figure B-5**: 1st, 10th, 25th, and 50th percentile results for scenarios AA07, AA10, AA08, and AA04, which represent Class A discharges reducing effluent NH34 at different levels while Class A' discharges NH34 = 1.5 mg/L.*

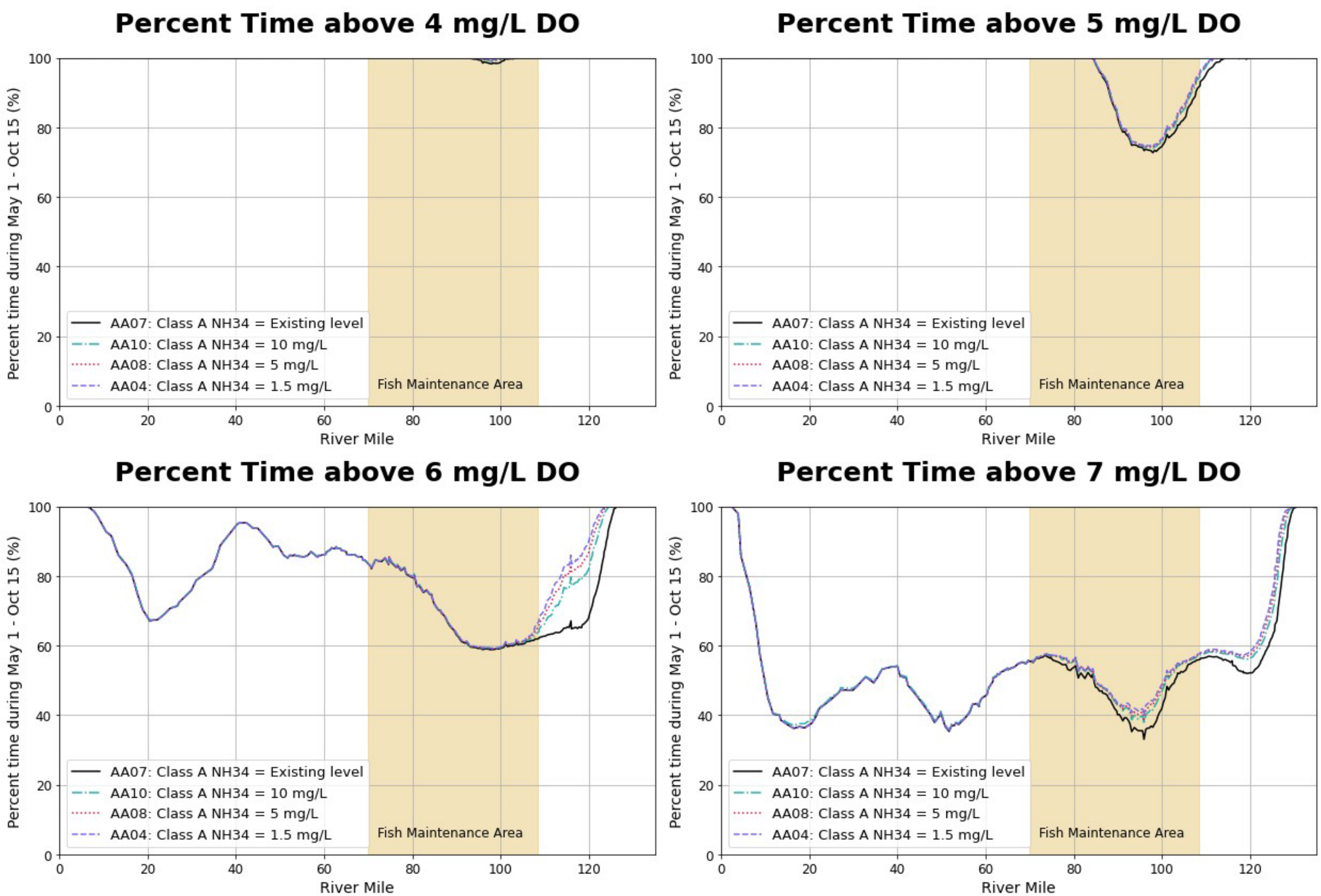

***Figure B-6**: Percent time above 4, 5, 6, and 7 mg/L for scenarios AA07, AA10, AA08, and AA04, which represent Class A discharges reducing effluent NH34 at different levels while Class A' discharges NH34 = 1.5 mg/L.*

Appendix C: Restoration Scenario Comparisons

- Comparisons between AA15 (restoration scenario) and AA01 (baseline)
- Visualizations of AA15 (restoration scenario) under different hydrologic conditions

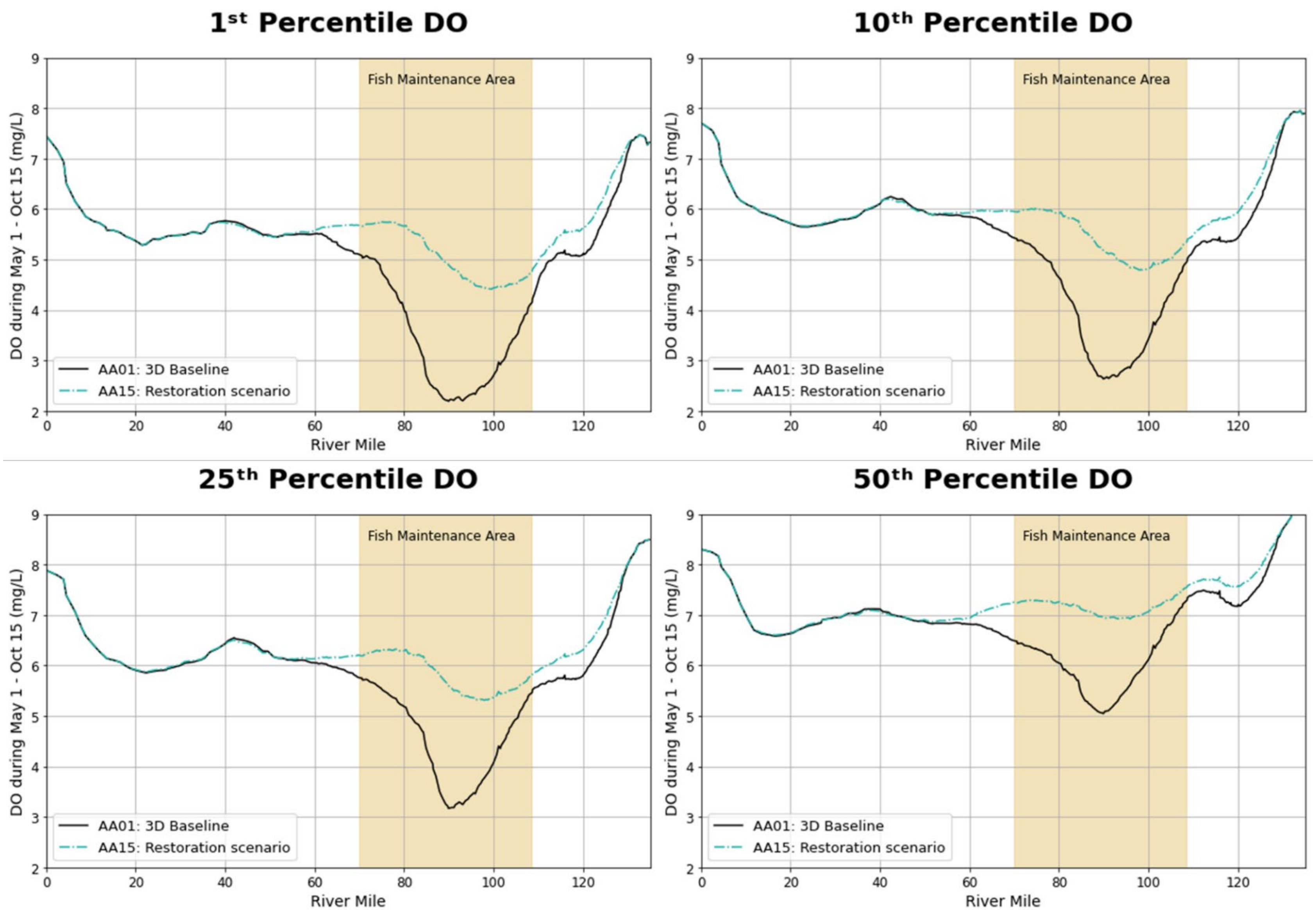

Figure C-1: 1st, 10th, 25th, and 50th percentile results for the baseline and restoration scenarios.

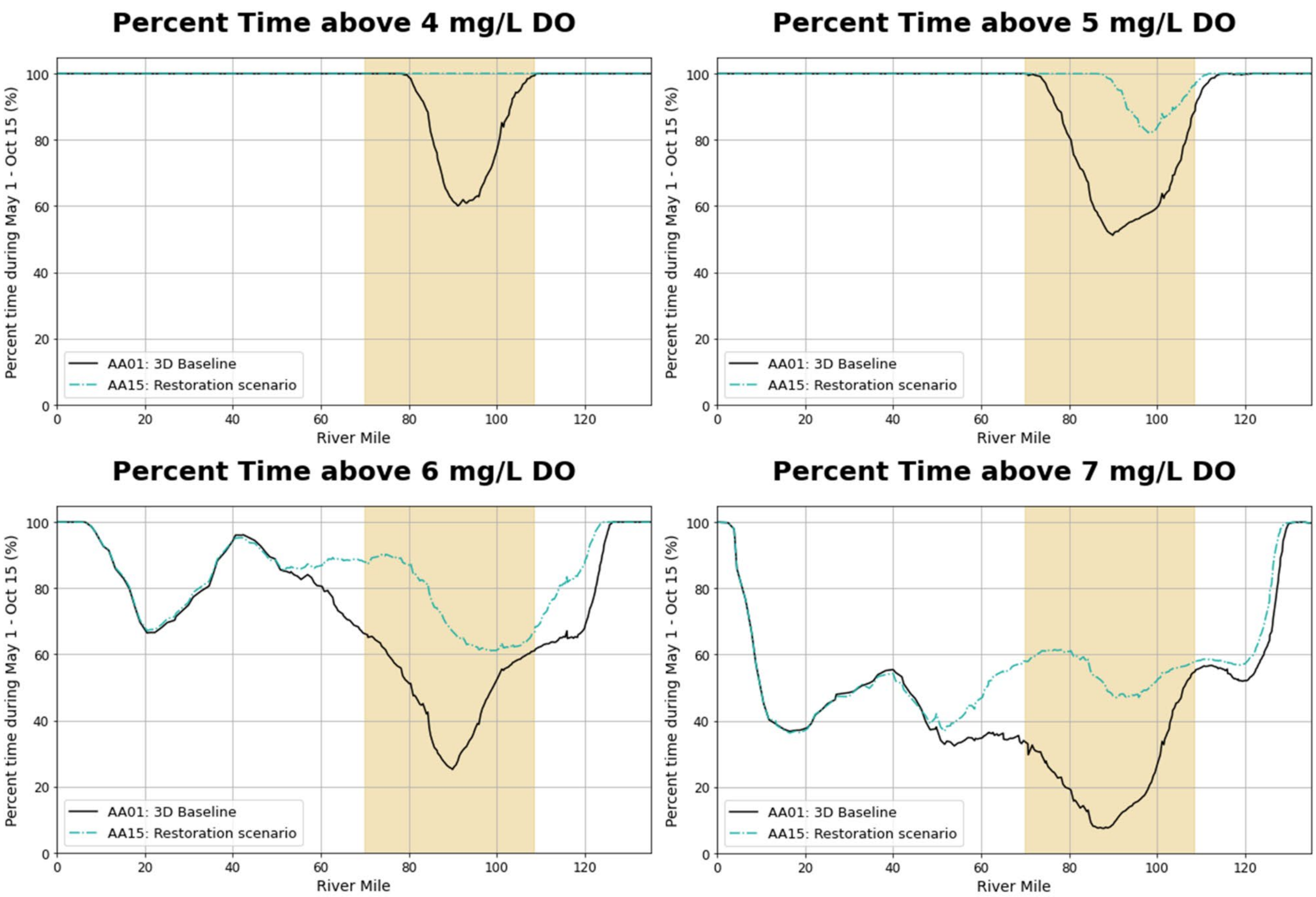

Figure C-2: ***Percent time above 4, 5, 6, and 7 mg/L for the baseline and restoration scenarios.***

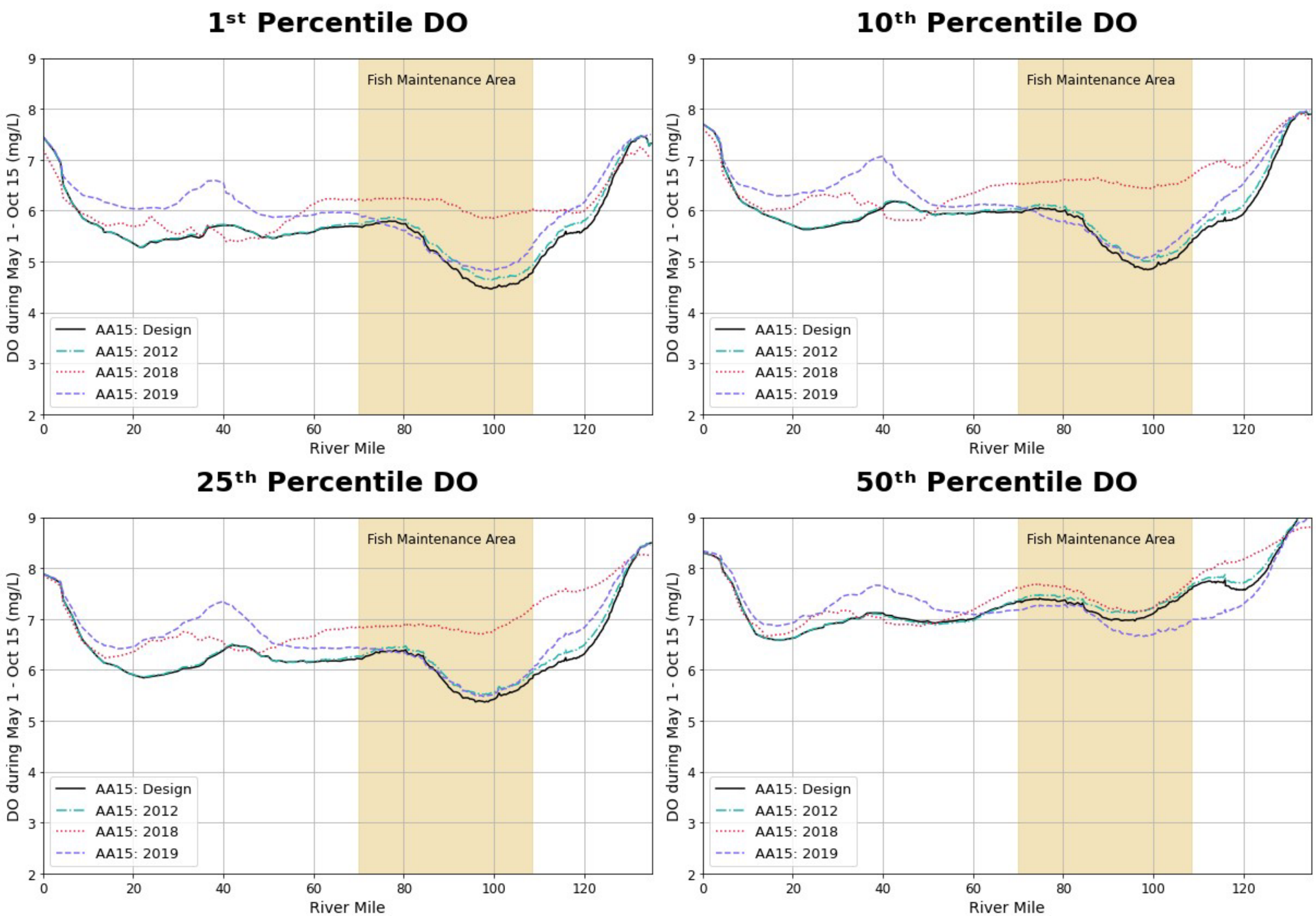

Figure C-3: 1st, 10th, 25th, and 50th percentile results for the restoration scenario AA15 run under different hydrologic conditions.

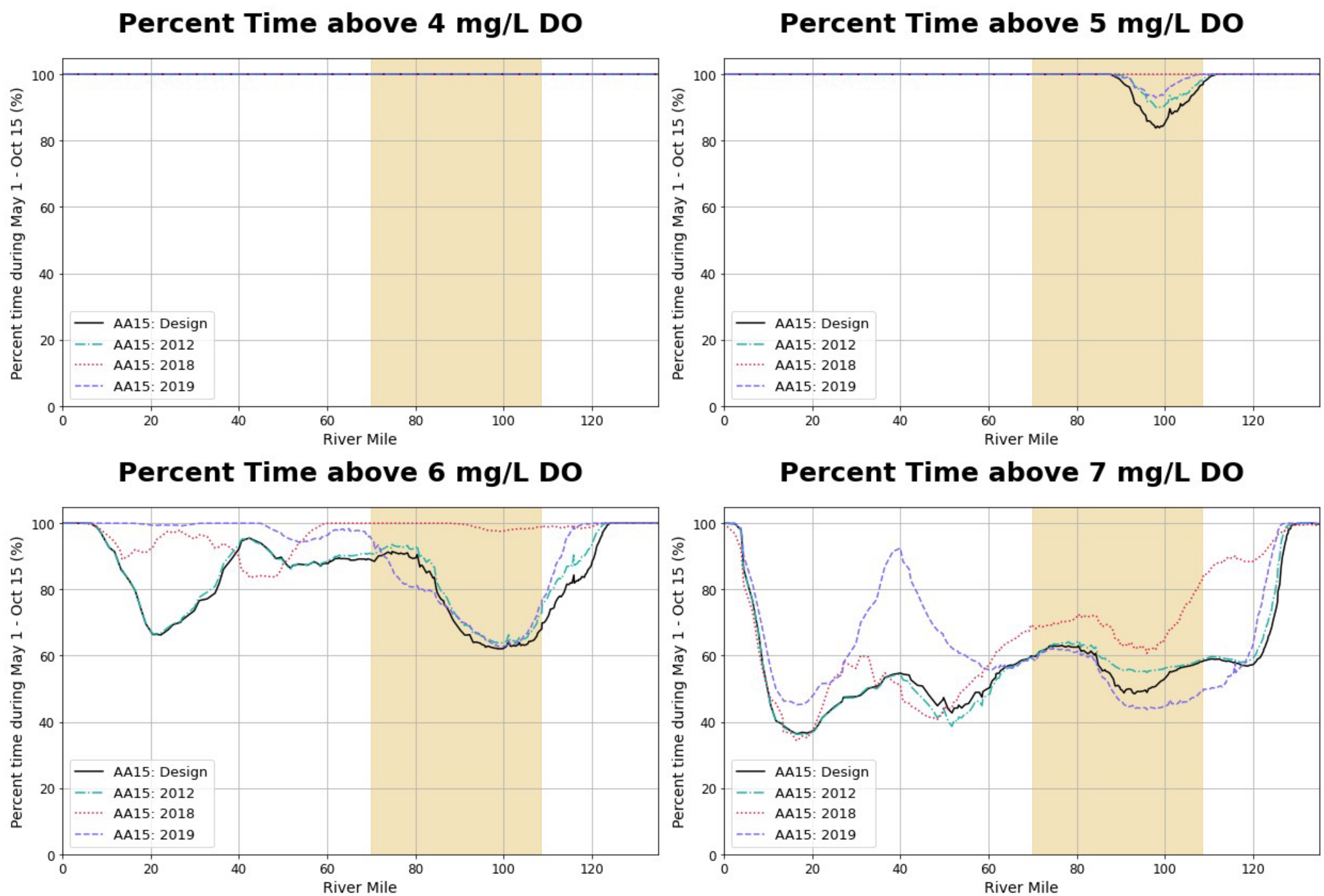

Figure C-4: Percent time above 4, 5, 6, and 7 mg/L for the restoration scenario AA15 run under different hydrologic conditions.

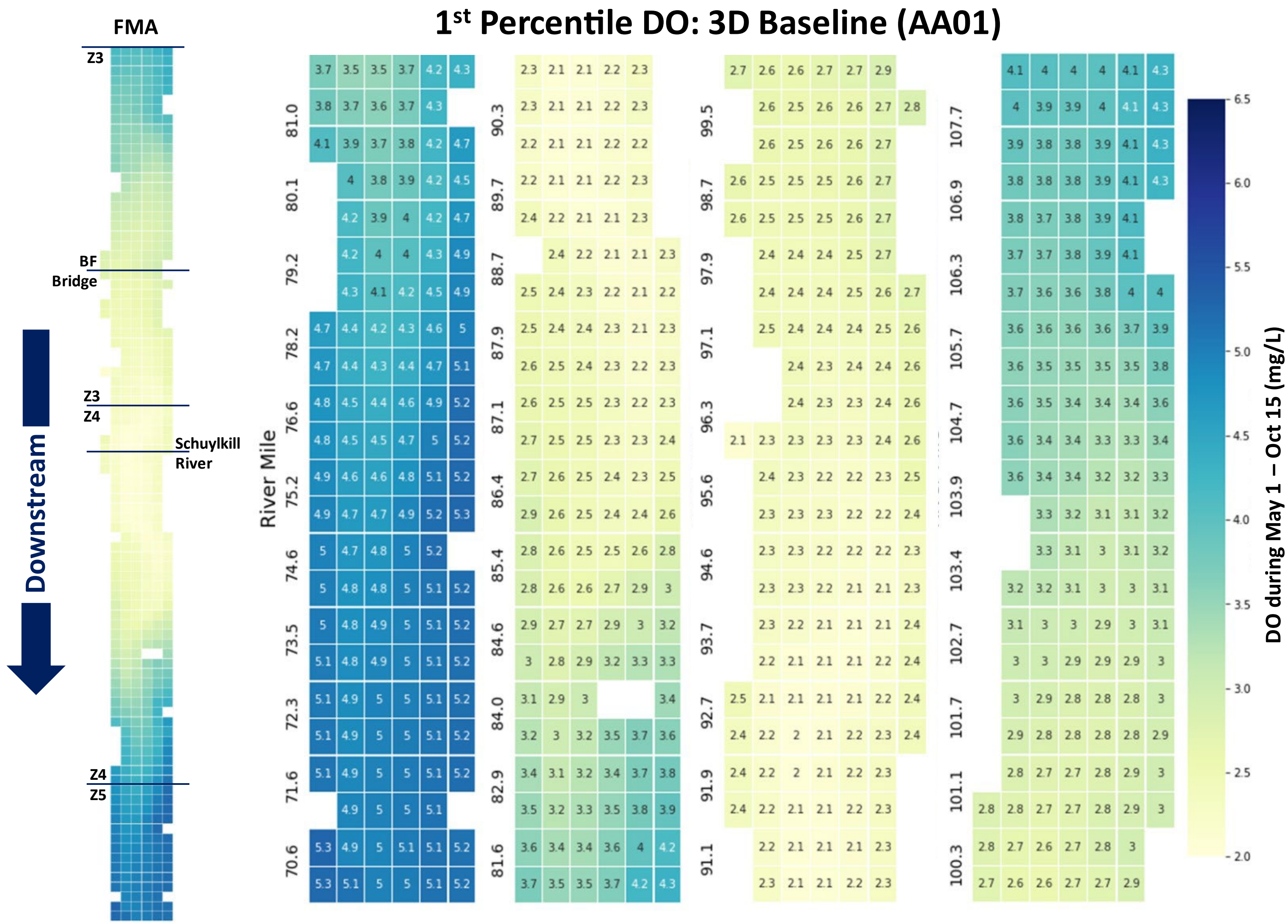

Figure C-5: Tabular maps displaying depth-averaged 1st percentile DO throughout the FMA for the baseline scenario.

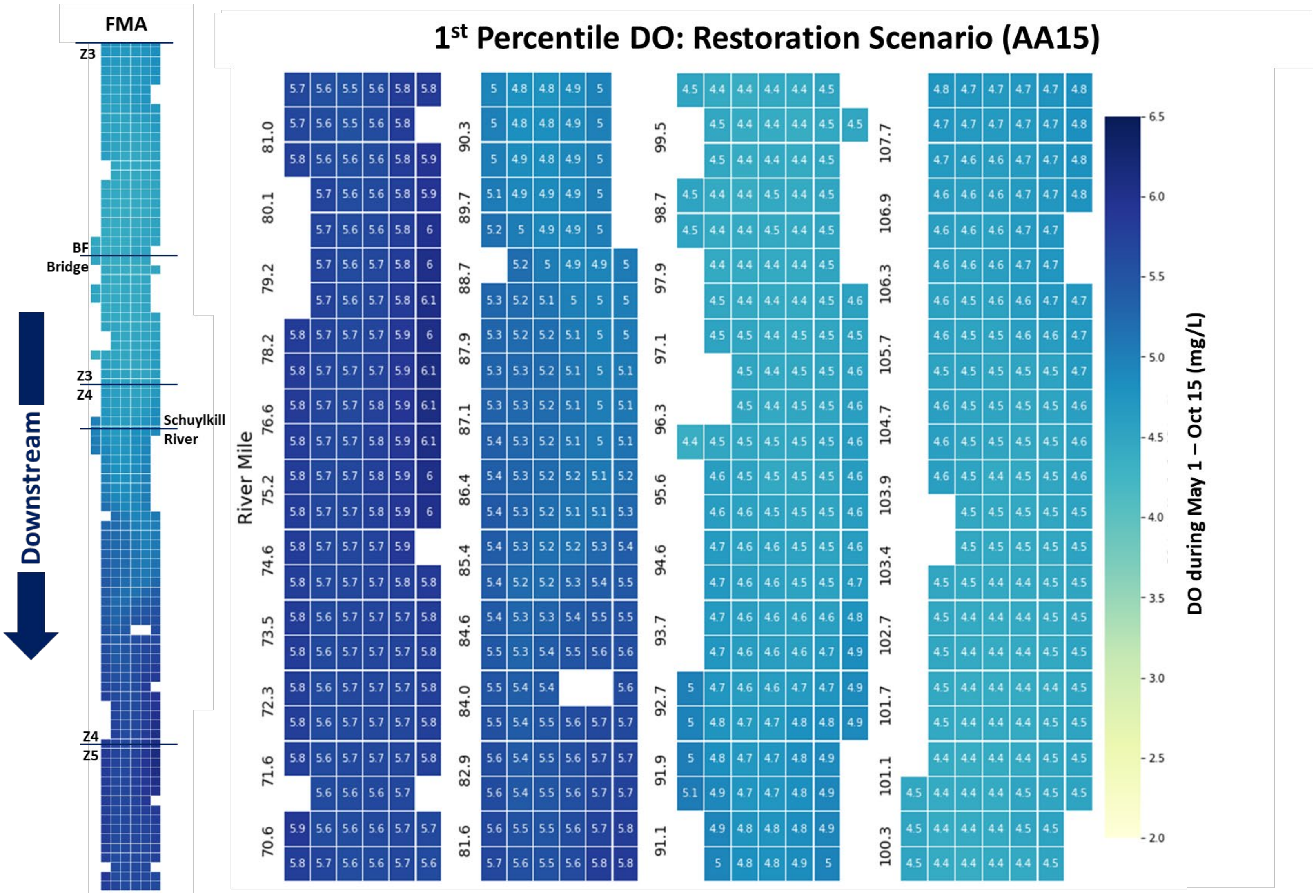

Figure C-6: Tabular maps displaying depth-averaged 1st percentile DO throughout the FMA for the restoration scenario.

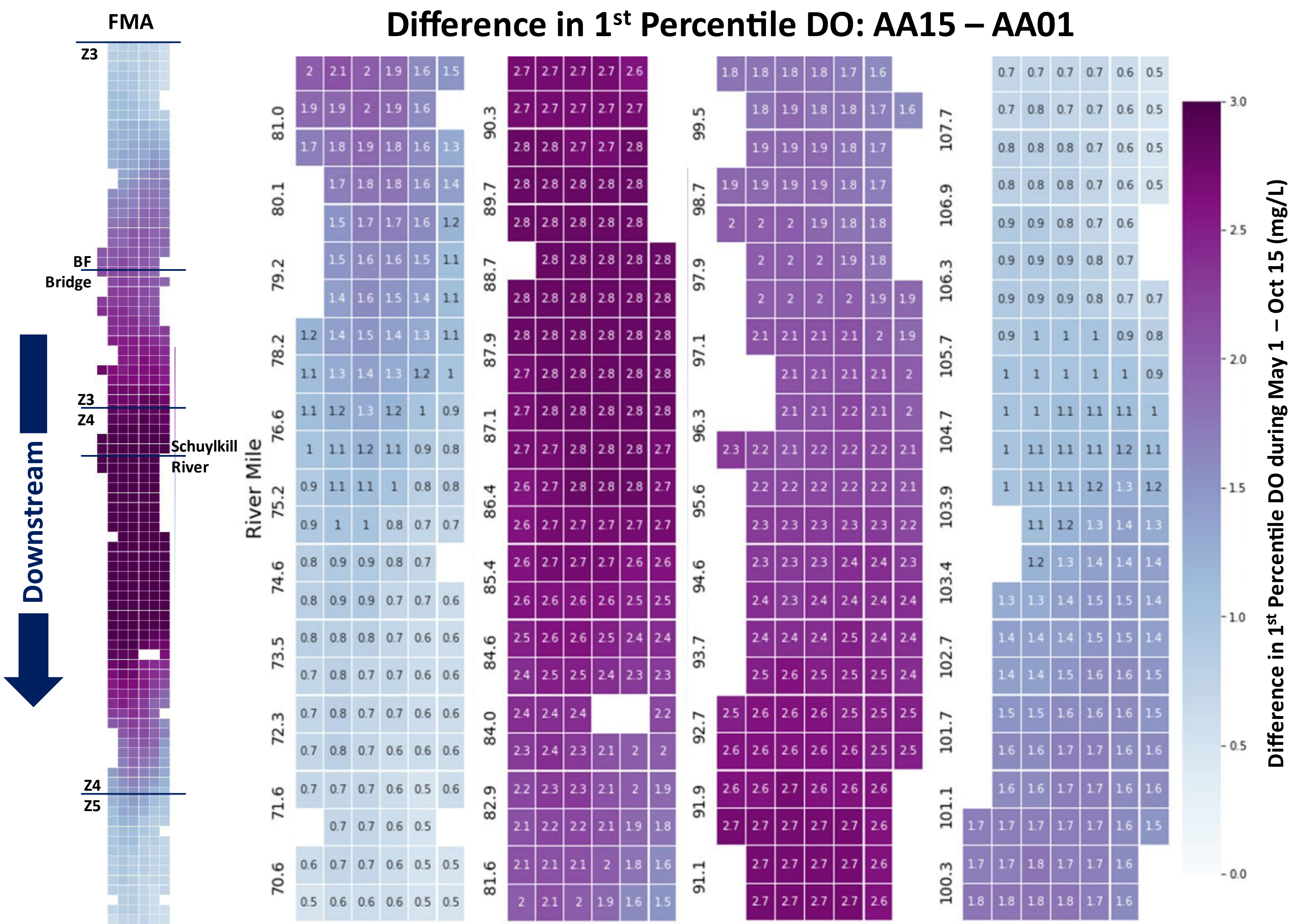

Figure C-7: Tabular maps displaying the increase in depth-averaged 1st percentile DO throughout the FMA for the restoration scenario relative to the baseline scenario.

Appendix D: Additional Model Scenarios for Economic Evaluation

DESCRIPTION OF ADDITIONAL MODEL SCENARIOS

Four additional scenarios were designed to serve as the basis for economic analysis of before ("baseline") and after ("policy") scenarios. These scenarios were designed specifically for the EPA to use in its rulemaking to revise the aquatic life use and supporting water quality criteria for DO in the FMA. The baseline and policy scenarios are called "Econ-Before" and "Econ-After" in this Appendix in order to distinguish them from the baseline and restoration scenarios discussed in the body of this report.

The Econ-Before effluent condition is similar to the baseline design condition (AA01) with the following two adjustments: PWD's planned sidestream treatment to reduce ammonia load from its Southwest Water Pollution Control Plant by approximately 25% is incorporated, as are expected CSO reductions in accordance with long-term control plans for the combined sewer systems of PWD, Camden County MUA, DELCORA, and City of Wilmington (Section 5.1.1).

The Econ-After effluent condition is similar to the restoration scenario (AA15) with the following two adjustments: summer effluent DO concentrations for the seven Class A' dischargers were assigned a constant value of 6.0 mg/L, and the same TN reduction from sidestream treatment in the Econ-Before effluent condition was applied. This TN adjustment was needed because PWD's sidestream ammonia treatment, implemented in the Econ-Before effluent condition, reduces effluent TN, but restoration-scenario reduction of effluent ammonia to 1.5 mg/L may not affect TN (it is assumed that NH34 is converted NO3; Section 4.1).

Two flow conditions were combined with the Econ-Before and Econ-After effluent conditions. The Design-Flow condition represents all 67 simulated wastewater treatment plants discharging at their permitted flow rate. One adjustment was made from the design condition applied in the restoration analysis: the DELCORA effluent flow rate was reduced from 70 MGD to 44 MGD, reflecting a recent decision to not pursue an expansion to discharge up to 70 MGD. The Actual-Flow condition represents all 67 simulated wastewater treatment plants discharging at their actual flow rates (Section 2.3.3).

Thus, the four additional scenarios are:

1. Econ-Before Actual-Flows
2. Econ-After Actual-Flows
3. Econ-Before Design-Flows
4. Econ-After Design-Flows

The following figures display results for these four scenarios for the year 2019.

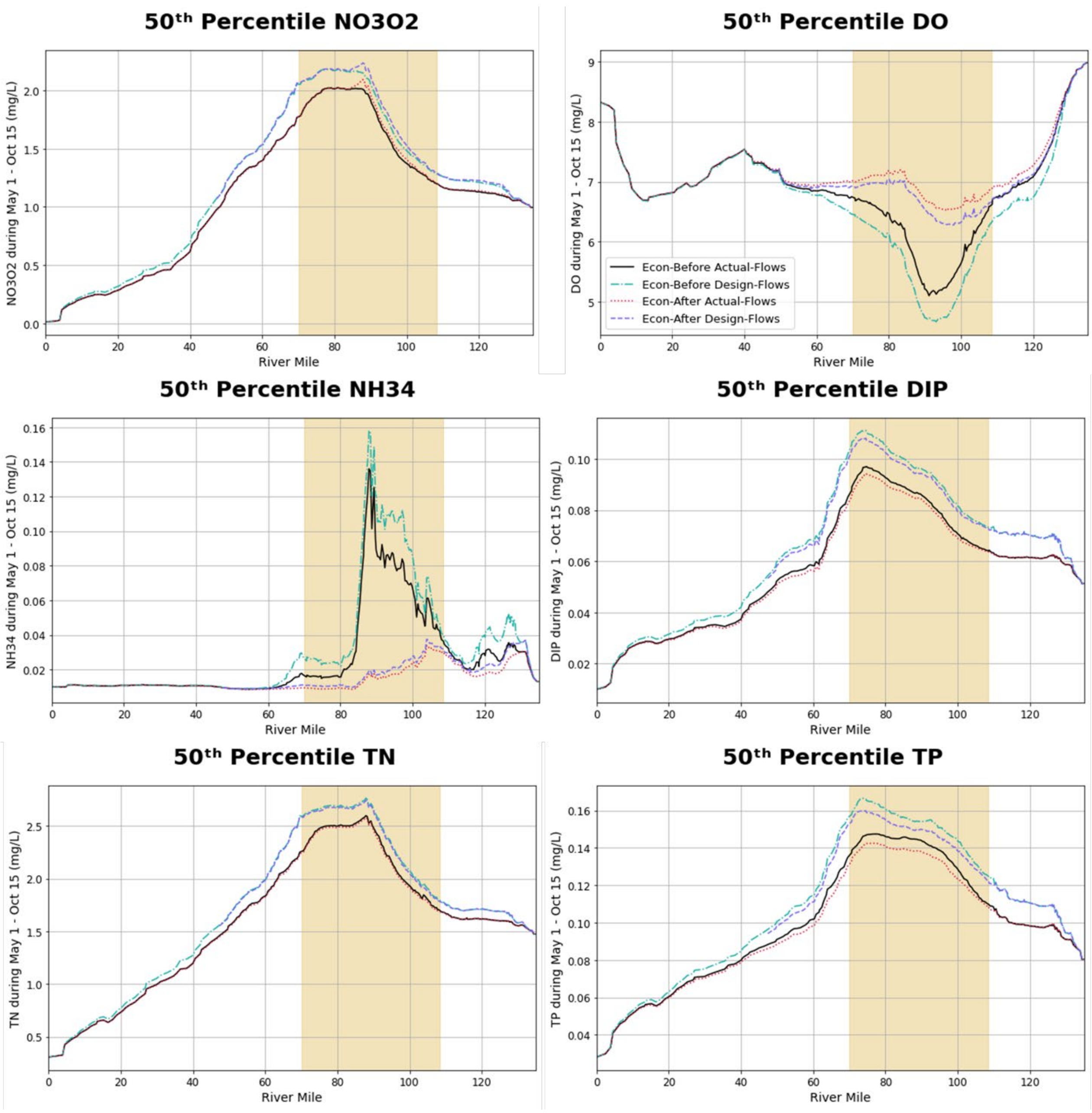

Figure D-1: 50th percentile NO3O2, DO, NH34, DIP, TN, and TP for the four additional scenarios.

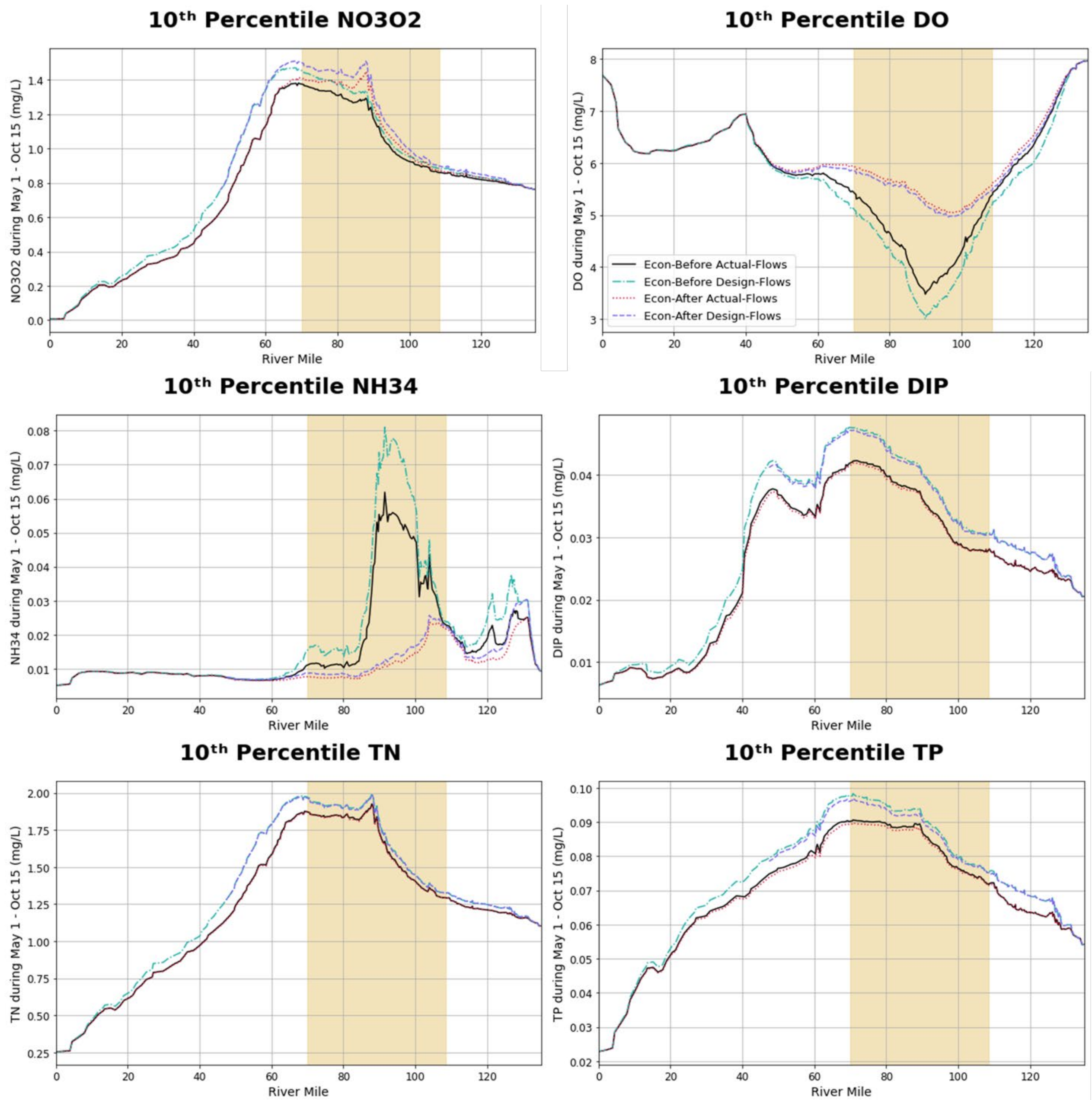

Figure D-2: 10th percentile NO3O2, DO, NH34, DIP, TN, and TP for the four additional scenarios.

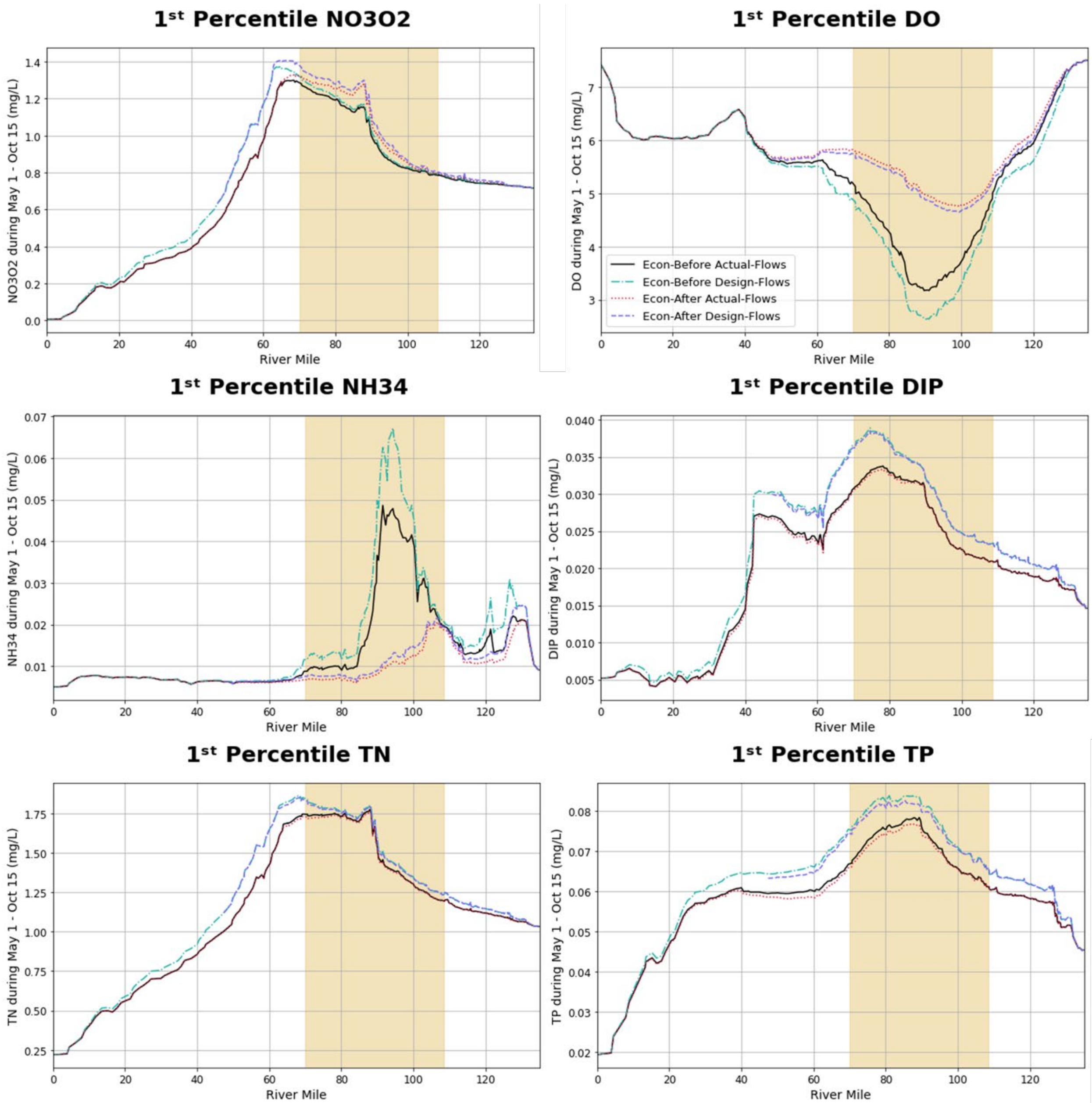

Figure D-3: 1st percentile NO3O2, DO, NH34, DIP, TN, and TP for the additional scenarios.