Technical Report for the Delaware Estuary and Basin

2017

Partnership for the DELAWARE ESTUARY

A publication of the Partnership for the Delaware Estuary—A National Estuary Program

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The Partnership for the Delaware Estuary leads science-based and collaborative efforts to improve the tidal Delaware River and Bay, which spans Delaware, New Jersey, and Pennsylvania.

Acknowledgments

Funding for development of the Technical Report for the Delaware Estuary and Basin was provided by the Environmental Protection Agency to the Partnership for the Delaware Estuary (PDE), under National Estuary Program Grant Section 320 Grant Funding. Additional assistance was provided by the William Penn Foundation. The Delaware River Basin Commission, University of Delaware, Pennsylvania State University, and Fishery Investigations, some of which led the analysis and interpretation for sections of this report.

This report was prepared by dozens of individual volunteers, representing diverse agencies, academic institutions, companies, and non-profit entities, who are listed as authors or contributors. Special thanks goes to Spencer Roberts and Ashley Chong whose assistance in the organization and compilation of this report was vital. Additional thanks go to those who graciously volunteered to review the entirety of this report before it's finalization: Kelly Somers and Kristin Reagan. We are also grateful to the PDE Science and Technical Advisory Committee and Estuary Implementation Committee for marshaling the necessary staff and resources to provide peer review.

Graphics

Cover photographs for this report were taken by staff of the Partnership for the Delaware Estuary, unless otherwise noted.

Aerial photography for maps are courtesy of National Agriculture Imagery Program (NAIP), unless otherwise noted.

Suggested Citation

Partnership for the Delaware Estuary. 2017. Technical Report for the Delaware Estuary and Basin 2017. L. Haaf, S. Demberger, D. Kreeger, and E. Baumbach (eds). PDE Report No. 17-07. 379 pages.

Abstract

The Technical Report for the Delaware Estuary and Basin (TREB) analyzes the best possible current data on the status and trends of more than 50 environmental indicators, including a diverse suite of water, habitat, and living resources. Taken together, the condition of these indicators reflects the overall environmental health of the Delaware River and Bay, and the watershed that drains into it. This report is produced every five years by the Partnership for the Delaware Estuary, a National Estuary Program, as the technical foundation for "State of the Estuary" reports for the public. There are eight key indicator categories: watershed land use, water quantity, water quality, habitats, living resources, climate change, and restoration progress. Scientists and managers examined historic, recent current, and predicted future changes in each indicator's status to develop an understanding of trends. Finally, this report describes future actions and needs that can strengthen indicator reporting and potentially improve environmental conditions. The results from this assessment suggest that the current health of the Delaware Estuary and River Basin in 2017 is "fair," reflecting a mix of positive and negative trends. The overall assessment of "fair" health is unchanged from TREB 2012 and the smaller State of the Estuary Report in 2008.

Table of Contents‡

‡Indicators updated for 2017 are in bold italics. Reference the Introduction for details.

Executive Summary

The purpose of the 2017 Technical Report for the Delaware Estuary and Basin (TREB) is to assess the overall environmental condition of the watershed by examining the status and trends of key indicators that reflect the health of its natural systems. Meeting this goal is challenging because the Delaware River Basin is a large and complex watershed, encompassing more than 35,000 square kilometers (>13,500 square miles) and extending from headwater streams and mountains in New York State, to the coastal plain, and out to the ocean near Cape May, NJ, and Cape Henlopen, DE.

The watershed is home to about 9 million people and supplies drinking water to another seven million in New York City and northern New Jersey living outside of the basin. Hundreds of plant and animal species live in balance with people in diverse habitats, including many ecological treasures. The region also has a storied history, starting with rich Native American peoples and extending through the birth of the United States and the Industrial Revolution, up to the present day where it continues to function as a nationally important economic center and strategic port.

Environmental indicators are aspects of the environment which can be quantified and are representative of prevailing local conditions. The approach used in this report was to gather, analyze and interpret the best and most recent data for a suite of more than 50 indicators that represent different facets of the natural ecosystem, such as water quality, living resources, habitats, and land cover. When considered together, this indicator-based report provides a comprehensive picture of the status and trends in environmental health of the Delaware Estuary and Basin.

The eight chapters of TREB are organized topically into the following sections: watersheds and landscapes, water quantity, water quality, sediments, aquatic habitats, living resources, climate change, and restoration. Each section includes a number of different indicators and was written by a different set of authors with science and management expertise relevant to the topic. For example, the climate change chapter considers long-term changes in air temperature, precipitation, extremes in air temperature and precipitation, snow cover, wind speed, stream flow, ice jams, and sea level.

For each indicator, authors present and interpret the most recent available status and trends data and summarize any actions or needs that could strengthen future indicator reporting, which will lead to improved environmental conditions. Examples of key findings in this report are summarized in the table on page 9 which shows both improving and declining environmental conditions. The list is not prioritized, and many more similar examples can be found in various report sections.

The results from this assessment suggest that the current health of the Delaware Estuary and River Basin in 2017 is "fair," reflecting a mix of positive and negative trends. The status of many indicators is good, and others are not so good. Trends for some indicators appear to be improving, while others appear to be worsening. The overall assessment of "fair" health is unchanged from TREB 2012 and the smaller State of the Estuary Report in 2008.

The information in this report should be interpreted carefully because changes in some indicators do not necessarily reflect declining or improving conditions per se, but instead reflect natural variability. For example, it is possible that some species or conditions are actually improving at the expense of others, due to complex ecological relationships. In some cases, this report effort was hampered because some components of the ecosystem that could serve as strong indicators were not able to be included due to insufficient data. The development of this report therefore allows us to assess not only the state of the environment, but also the state of our knowledge and understanding. Furthermore, the restoration chapter attempts to assess our management progress in preserving, enhancing and restoring environmental conditions, rather than the environmental conditions per se (which is the focus of most of the rest of this report).

Although the "fair" overall health assessment is unchanged since 2008, it reflects substantial improvement compared to earlier decades for many key indicators. For example, advances in wastewater treatment and implementation of the Clean Water Act led to dramatic improvement in dissolved oxygen in the river's urban corridor over the past 30 years. Unfortunately, the continued loss and degradation of important habitats and impacts from climate change have undermined the recent recovery and efforts to protect and restore the system. The continued expansion of human activities is likely to increasingly tax our natural resources and require management diligence, especially with regard to water withdrawals, forest cutting, wetland loss, and development. These challenges will be exacerbated by a shifting climate, especially increasing temperature, precipitation, sea level, and salinity.

Where possible, the future status and trends of indicators are also discussed in the context of the expected increase in human activities and climate change. As one example, warming water (from climate change) holds less dissolved oxygen, which is vital for aquatic animals such as fish. Oxygen deficits can also be exacerbated by excess nutrients from runoff, which fuel microbial respiration. With increased water temperature and potentially greater nutrient runoff from more people, it is plausible to expect the trajectory of past improvements in dissolved oxygen conditions to reverse course, requiring even more effort to manage dissolved oxygen than in the past due to changing conditions. Similarly, increasing sea level and wind fetch could interact with bigger waves from larger ships to hasten erosion of coastal wetlands that help to sustain water quality. This report includes many other similar examples of past successes, ecological interactions, and emerging threats.

The cumulative impacts to natural resources from both anthropogenic alterations and shifting climate conditions are difficult to predict. Hence, continued careful monitoring of the indicators reported here will be critical so that environmental managers can make informed decisions to sustain crucial life-sustaining ecosystem services, which are worth billions of dollars per year. Specifically, to address future environmental challenges while preserving prosperity in the region, agencies, scientists, and others must work together to:

- Sustain and strengthen the effectiveness of monitoring, protection and restoration efforts by focusing on a set of shared, strategic priorities
- Set science-based goals that plan for change as part of the natural landscape
- Adopt realistic environmental targets that focus on preserving and enhancing key life-sustaining features
- Apply an ecosystem-based approach to management that considers cumulative impacts
- Facilitate collaboration among states and sectors to implement the Comprehensive Conservation Management Plan of the Delaware Estuary Program, through the congressionally designated National Estuary Program for the Delaware River and Bay.

The information, perspectives and future needs stated in this report reflect the best current scientific consensus of the authors that drafted individual sections and do not necessarily represent the official views of the Partnership for the Delaware Estuary, other members of the Delaware Estuary Program, or any other participating entity or specific author. This report is a collective, peer reviewed effort which attempts to coordinate a consistent style and content among sections. However, the written presentations and depth of analysis will reflect (or vary in accordance with) the availability of data, methods of presentation, analytical rigor and writing styles that are appropriate for different fields and various authors.

Table 0.1 Top positive (A) and negative (B) findings from the 2017 Technical Report for the Estuary and Basin, as judged by the Science and Technical Advisory Committee and this report's authors. Impact scores are qualitative and based on 1) novelty of the finding for the 2017 reporting period, 2) relative overall impact to estuary and basin wide health, and 3) immediacy of action need. Impact scores of 1 for positives are very good, whereas a score of 6 for a negative is near detrimental. Averaging all impact scores yields a total score of 3.66, or an overall "fair" for the reporting period's estuary and basin health.

A.

Chapter	Positives		
	Indicator	Condition	Impact
Watersheds	Ecosystem Services	Worth >$12 billion annually	1
Water Quantity	Consumptive Use (Public)	Declined per capita 1990-2014	2
Water Quality	Dissolved Oxygen	Increased dramatically 1960s to present	1
Sediments	Total Organic Carbon	Decreased, suggesting lower organic pollution	2
Aquatic Habitats	Fish Passage	>160 km now accessible on the Lehigh River and Schuylkill	1
Living Resources	Striped Bass	Once nearly extirpated, the current population is a major spawning stock	1
Climate	Ice Jams	Decreased over period of record	2
Restoration	Habitat Type	Progress among types matches current priorities	3

B.

Chapter	Negatives		
	Indicator	Condition	Impact
Watersheds	Land Cover	Development continues to increase; forest acreage continues to decline	6
Water Quantity	Consumptive Use (Industrial)	Increased about 20% between 1994-2014	5
Water Quality	Nutrients	Nitrogen remains high relative to other estuaries	5
	Contaminants	Exceeds risk thresholds for consumption of many fish	5
Sediments	Sediment Budget	Sediment removal exceeds inputs, possibly impairing estuary habitats	6
Aquatic Habitats	Tidal Wetlands	Acreage decreased >1.5% 1996-2010, mainly from salt marsh loss	5
Living Resources	Atlantic Sturgeon	Despite young of year fish seen in 2009, the species is now federally endangered	6
	Freshwater Mussels	Abundance and range continues to decline	5
Climate	Precipitation	Increased, especially in the past 30 years, increased flooding	4
Restoration	Funding	Investment is very low compared to other large estuaries	6

Introduction

The construction of the 2017 Technical Report for the Delaware Estuary and Basin (TREB) was led by the Partnership for the Delaware Estuary's Science and Technical Advisory Committee (STAC; Fig 0.1) in collaboration with many other contributing scientists and managers. Core members of the STAC include professionals from: Delaware River Basin Commission, Delaware Department of Natural Resources and Environmental Control, New Jersey Department of Environmental Protection, Pennsylvania Department of Environmental Protection, Philadelphia Water Department, and Partnership for the Delaware Estuary. Other authors, contributors and reviewers represented dozens of academic, non-profit, and private business organizations.

Figure 0.1 The Science and Technical Advisory Committee. Photo credit: Angela Padeletti, Partnership for the Delaware Estuary

The 2017 TREB reviews the status and trends in extent or health of 50 environmental indicators as a way to systematically gauge the current health of the Delaware Estuary and Basin. Environmental indicators are specific, measurable markers that are used to assess the condition of the environment and indicate whether conditions are improving or worsening over time[1]. Additionally, indicators help raise awareness about important environmental issues, serve as tools for evaluating the effectiveness of management actions, and can function as early warning signals for detecting adverse changes in environmental quality[1]. Indicators were reviewed based on data availability and the indicator's ability to relate something important about the status of the natural resources, water quality, and climate conditions of the Delaware Estuary and its watersheds.

The final list of indicators chosen for study evolved over the course of several years, starting in 2006, but becoming more refined for technical reporting by the end of 2008. The 2008 State of the Estuary report paved the way for a more comprehensive technical effort with the 2012 TREB, which included status and trends data for more than fifty indicators, along with data analyses and interpretation. These indicators were selected and grouped based on consensus by the STAC and core members of the Delaware Estuary Program. The 2017 TREB includes updated data and a richer analysis for 46 of the 58 indicators (79%) reported in the 2012 TREB, and these updated indicators are denoted with bold font in the Table of Contents. Most of the indicators from 2012 that were not updated lacked available new data, and in a few cases a better indicator was developed that replaced the earlier indicator. Hence, this 2017 TREB includes the most current, comprehensive list of trackable metrics which professionals throughout the region find important, useful, and indicative of not only the ecological health of the estuary, but also of the way that the human population inhabiting the area interacts with these valuable resources

The purpose of this report is to synthesize the most recent status and trends data into a technical report, which can serve as the basis for translation products such as State of the Estuary Reports (PDE) and State of the Basin Reports (DRBC) that are periodically written for the public. Although data and analyses were not able to be obtained for some important resource conditions, the balance of indicator data covered in this report reflects the best possible regional perspective on overall environmental status and trends in the Delaware Estuary and Basin.

TREB results are also vital for measuring the progress made toward implementing the Comprehensive Conservation and Management Plan (CCMP) for the Delaware Estuary. By tracking indicators and assessing their status and trends every 5 years, periodic revisions and updates to CCMP goals and actions can be responsive to changing conditions. To assist with CCMP updates and guide environmental managers and

1. U.S. EPA. 2007. Indicator Development for Estuaries. EPA842-B-07-004. Available at: http://www.epa.gov/owow/estuaries

scientists, this report lists future "Actions and Needs" for each indicator. In many cases, these actions and needs call for improved coordination and/or monitoring. Where data are currently incomplete or unavailable, PDE and partners will work to sustain and improve monitoring to address data gaps and facilitate data sharing and management.

Organization of the Technical Report for the Delaware Estuary and Basin

The sample frame for TREB is the entire Delaware River Basin, although the focus for some indicators is particular sub-watershed areas such as the Delaware Estuary which forms the lower half of the Delaware River Watershed (HUC#0204) (see Fig 0.4). Indicators are grouped into eight chapters, beginning with watershed traits and land use in Chapter 1. The watershed regions considered in this report extend from headwater streams in New York to the mouth of Delaware Bay between Cape May, NJ and Cape Henlopen, DE.

Water resource indicators are next discussed in Chapters 2 and 3, followed by sediment indicators in Chapter 4. Habitat-related indicators are examined in Chapter 5, distinguishing among subtidal, intertidal (Fig. 0.2A and B) and nontidal habitats (Fig 0.2C). Living resources are in Chapter 6, summarizing status and trends of key animals that live in the estuary or river (Fig. 0.2D). Chapter 7 is dedicated to tracking changes in climate-related conditions (Fig. 0.2E). Whereas Chapters 1-7 focus on status and trends in specific environmental conditions, Chapter 8 discusses indicators that track the progress of environmental protection and restoration efforts (Fig. 0.2F).

Figure 0.2 TREB indicators photo collage. Photo credits: Partnership for the Delaware Estuary staff.

How to Use the Technical Report for the Delaware Estuary and Basin

For information on the status and trends of any specific indicator (e.g., American eels), refer to the appropriate section. To obtain an overall status summary for the Delaware Estuary and Basin, one can refer to the executive summary although we recommend reviewing the entire report. Many indicators interact through complex physical, chemical and biological relationships, and a complete review facilitates a fuller understanding of the status of functional interrelationships (i.e. how the system is working) rather than the abundance of single structural elements (i.e. how much of one parameter is present). For example, the population abundance of some fish species may depend on others through predation or competition relationships (e.g. striped bass versus weakfish - both are never abundant at the same time). Suspended sediment in the water can be a pollutant (e.g. in nontidal tributaries) or an essential limiting resource (e.g. for tidal wetlands), depending on the perspective.

No single indicator or chapter is diagnostic of overall environmental conditions. With respect to water quality, for example, there has been dramatic improvement in dissolved oxygen conditions since the 1972 Clean Water Act, which resulted in widespread upgrades to wastewater treatment and other remedies. On the other hand, the system remains saddled with legacy contamination resulting from being the seat of the American Industrial Revolution, and some types of pollutants such as nitrogen continue to increase.

The Delaware Estuary and Basin also has many unique facets, such as having globally rare tidal freshwater ecosystems. Naturally high turbidity in part of the estuary is thought to help stem eutrophication problems by light shading of phytoplankton blooms, despite high nutrient loadings. By cross-comparing results among chapters and reading authors' narratives, one can obtain a better understanding of the system's unique features and complex interactions. Taken together, analysis of all chapters provide the best possible basis for determining key status and trends of environmental conditions in the Delaware Estuary and Basin.

Regional Divisions of the Delaware Estuary and Basin

To simplify status and trend analyses, the Delaware Estuary and Basin are divided into four different "watersheds" or "regions". Additional geospatial resolution (e.g. sub-watersheds) varies among indicators, depending on the coarseness of datasets and scientific intent. Geospatial resolution of sub-regions therefore varies from course (e.g., nontidal versus tidal; Fig 0.4) to moderate (e.g., ten sub-watersheds; Fig 0.5 and Fig 0.6) to fine (e.g., twenty-one sub-regions similar HUC12s; Fig 0.7).

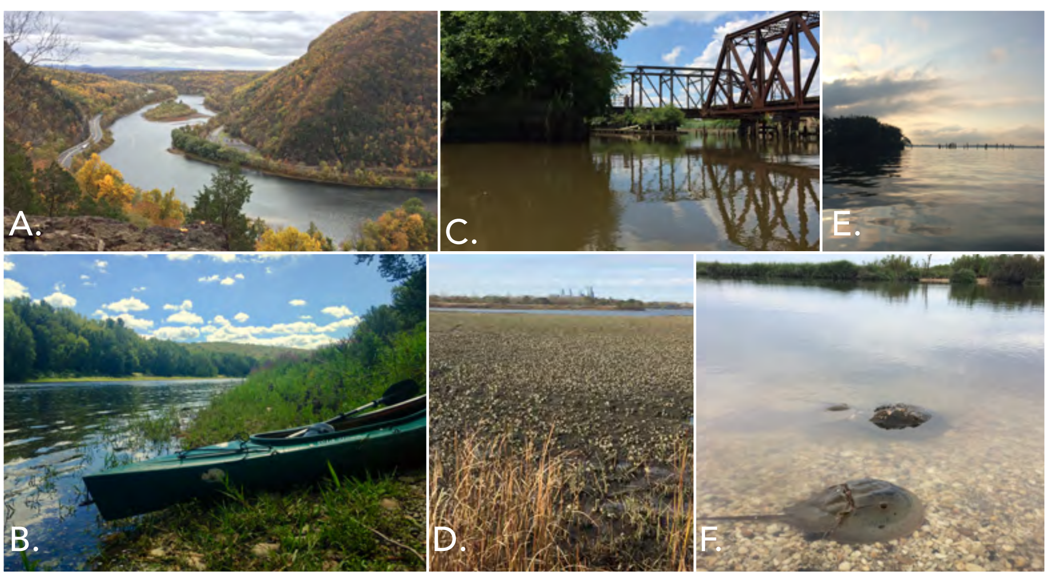


Figure 0.3 Examples of the various sub-regions (see Fig. 0.5) of the Delaware Estuary and Basin: the Delaware Water Gap (A and B, Central), the Christina River, DE (C, Lower), the view of Philadelphia, PA from Pennsauken, NJ (D, Lower), Pennsville, NJ (E, Lower), and horseshoe crabs in Egg Island, NJ (F, Bayshore). Photo credits: Partnership for the Delaware Estuary staff.

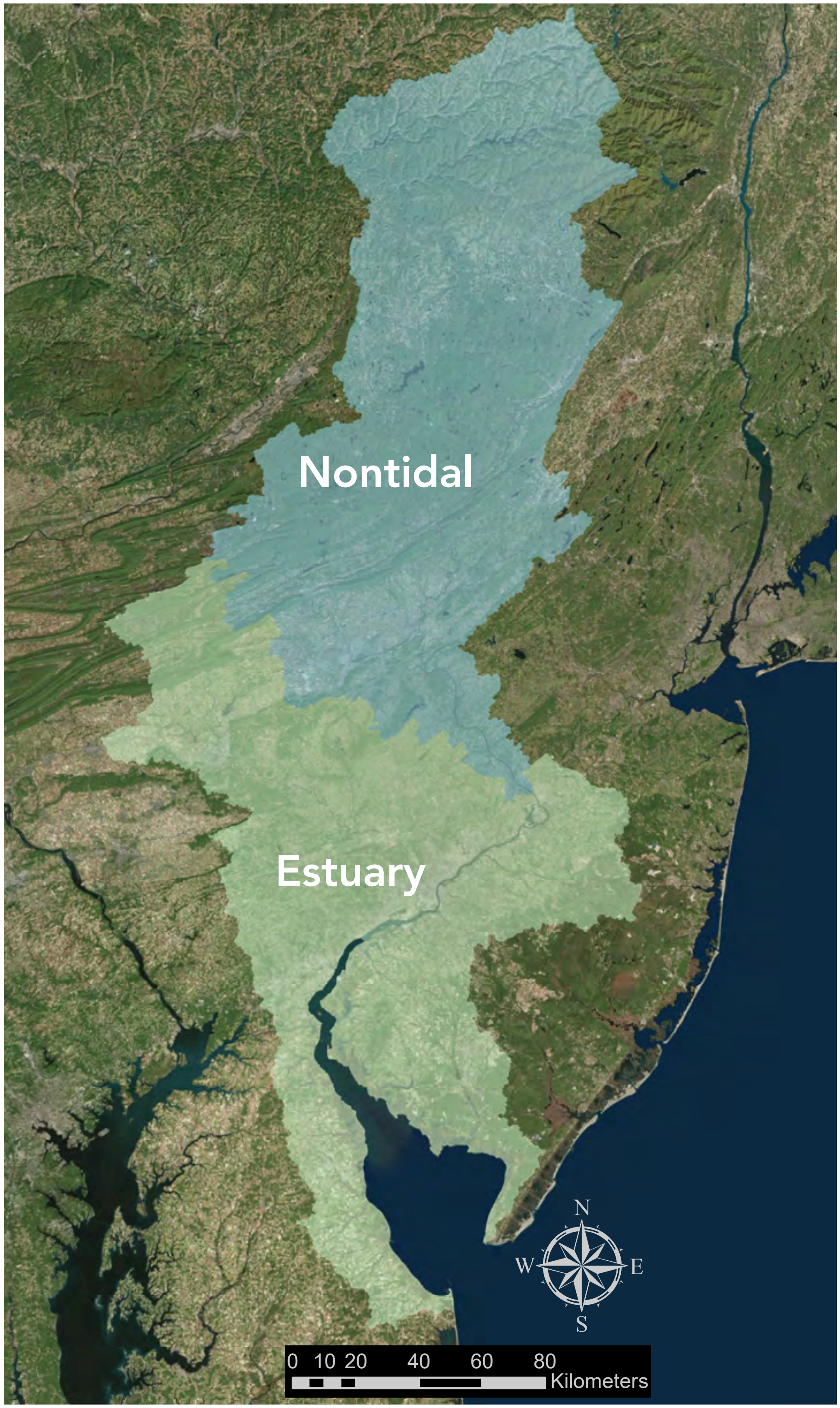


Figure 0.4 The Nontidal and Estuary divisions of the Delaware Estuary and Basin.

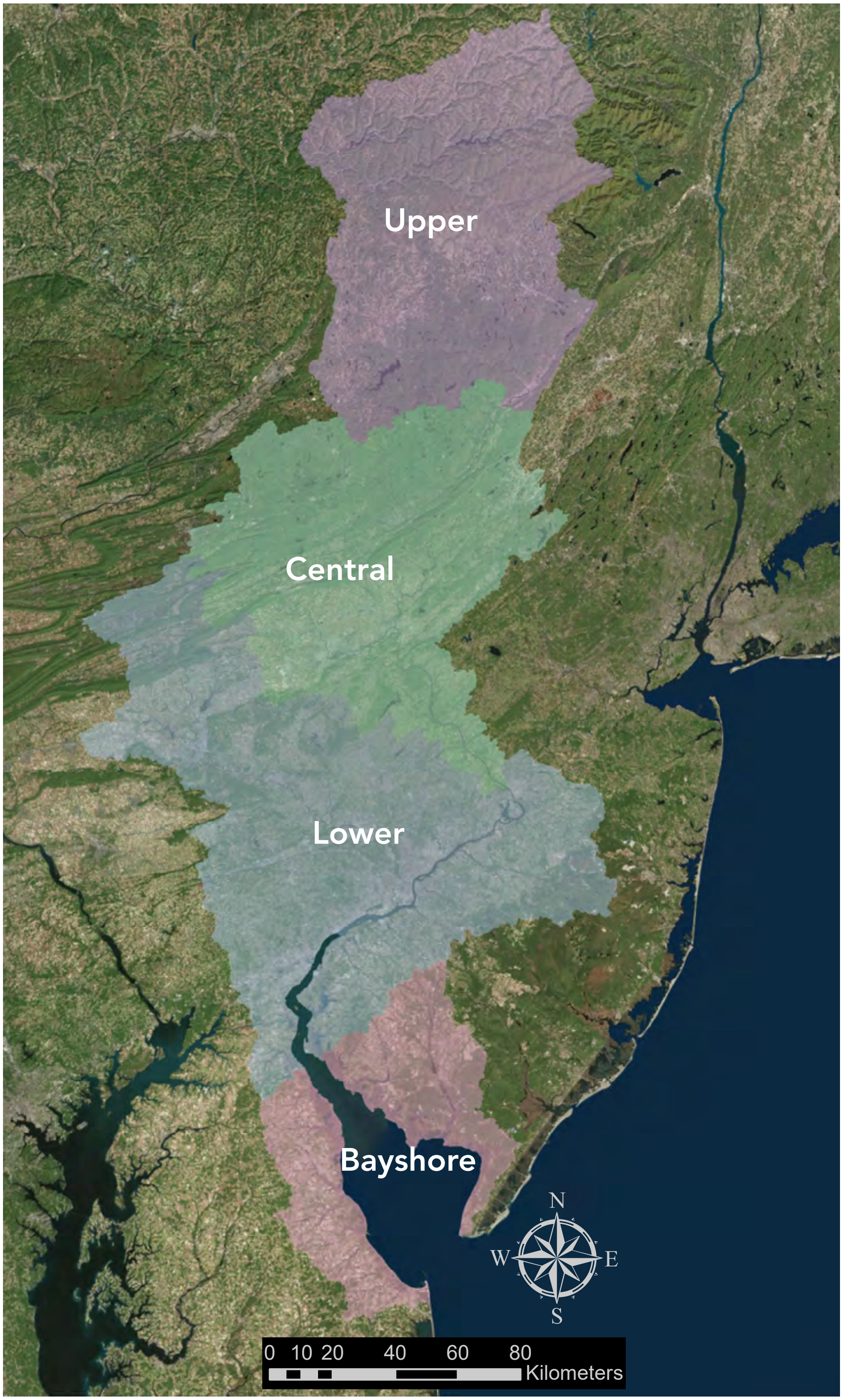


Figure 0.5 The four regions of the Delaware Estuary and Basin.

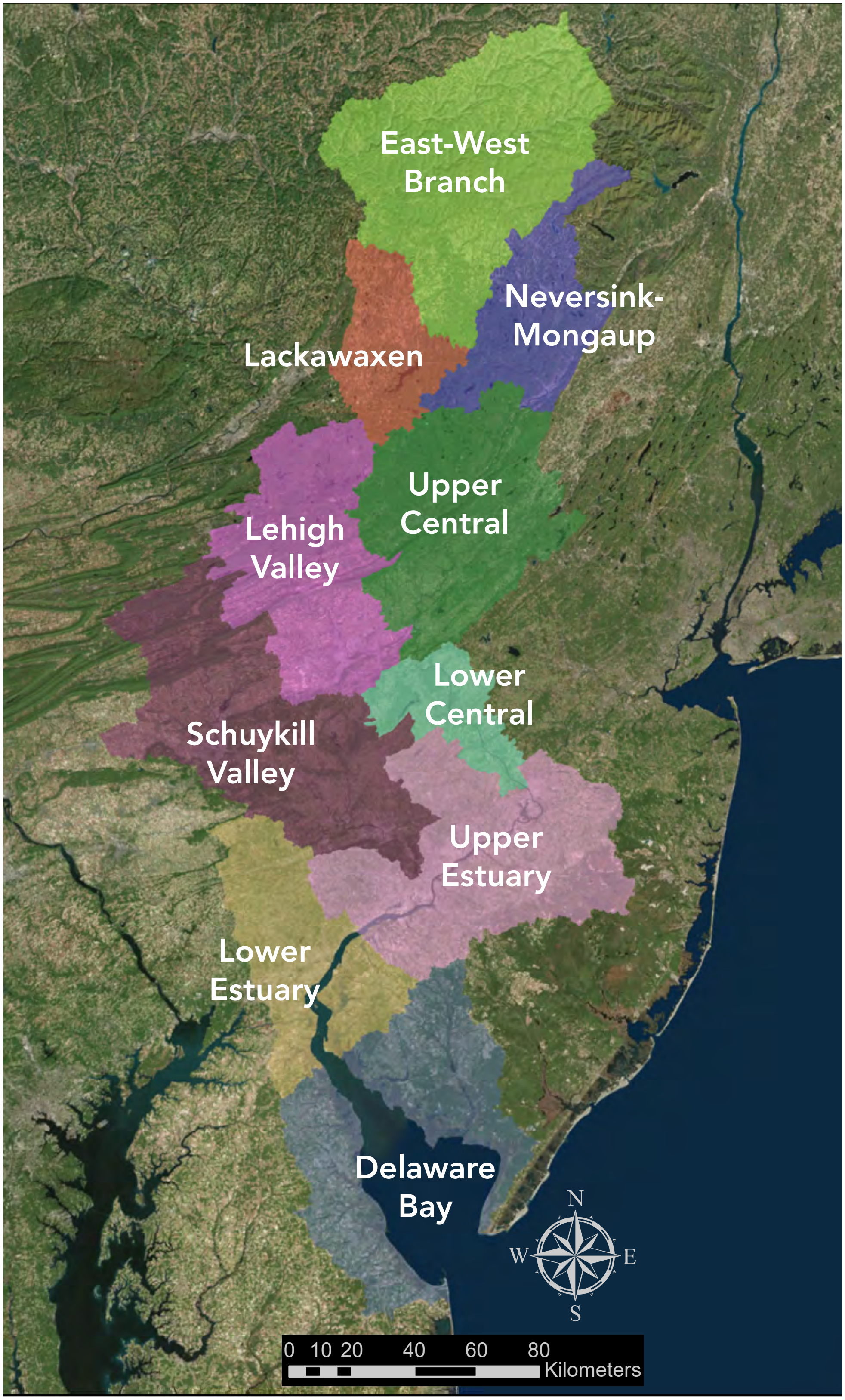
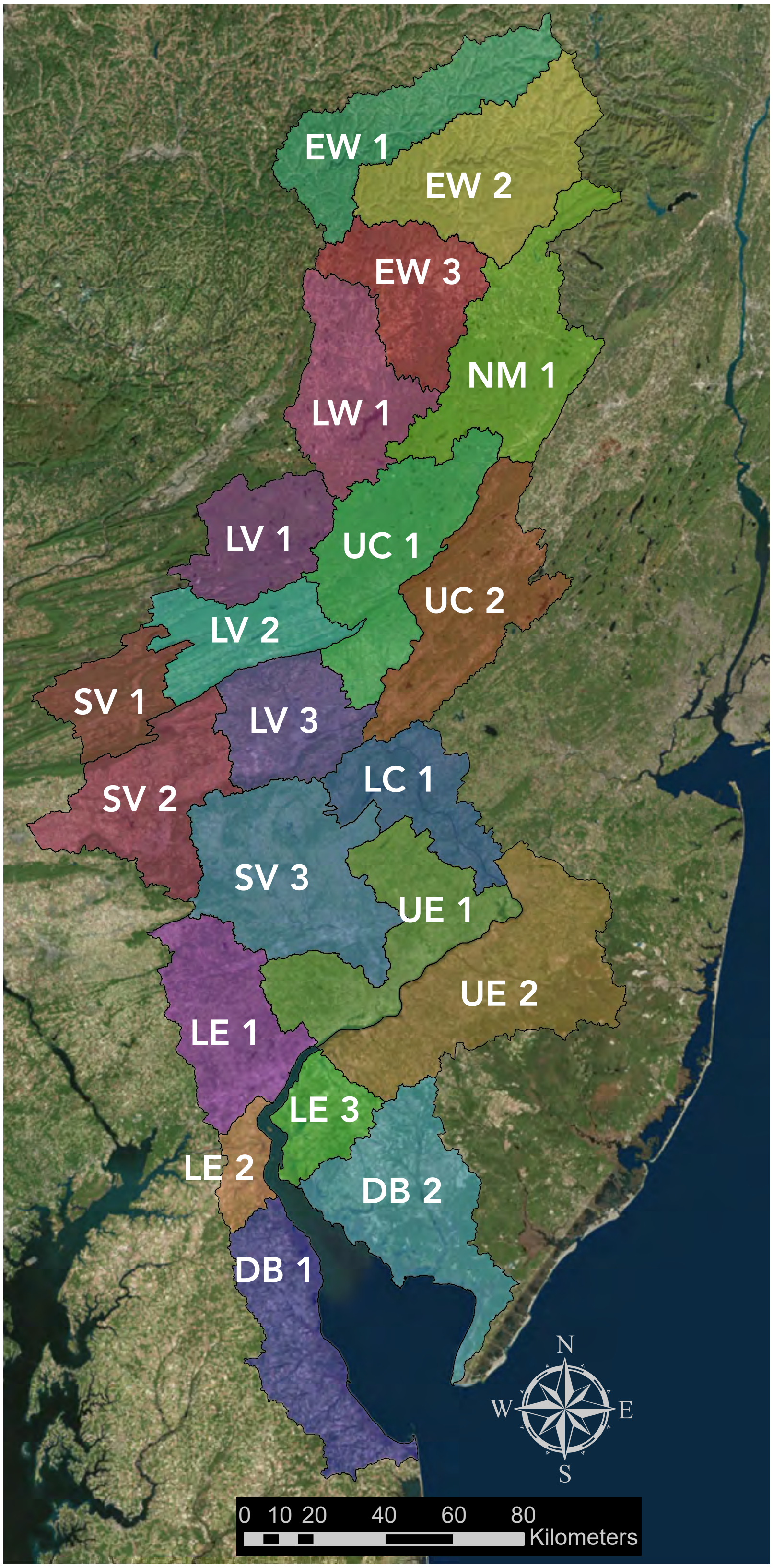


Figure 0.6 The ten subregions of the Delaware Estuary and Basin.



Label Legend

DB - Delaware Bay

EW - East-West Branch

LC - Lower Central

LE - Lower Estuary

LV - Lehigh Valley

LW - Lackawaxen

NM - Neversink-Mongaup

SV - Schuylkill Valley

UC - Upper Central

UE - Upper Estuary

Figure 0.7 The 21 watersheds of each subregion within the Delaware Estuary and Basin.

Chapter 1 - Watersheds and Landscapes

Partnership for the DELAWARE ESTUARY

December, 2017 | Report No.17-07

A publication of the Partnership for the Delaware Estuary—A National Estuary Program

1. Watersheds and Landscapes

1.1 Population

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1.1.1 Description of Indicator

Population is the total number of people in a given area. This indicator quantifies the human population within the Delaware River Basin based on data from the American Community Survey and the U.S. Census, Decennial Census and American Community Survey 5-year estimates 2011-2015. The size of the population is important to managers in the region because water quality (pollution) and quantity (water supply and flooding) impacts are directly proportionate to the number of inhabiting people. Population growth will increase demands on infrastructure and will spur development, resulting in increased impervious surfaces and runoff. Change in population aids the prediction of shifts in land cover types. As population increases, increasing demands on the land will lead to the conversion of forest and agricultural land to more developed uses. As agriculture land is developed, there is also more pressure on forested land to be converted to agriculture.

1.1.2 Present Status

The Delaware River Basin occupies 12,770 square miles (not including the open water of the River and Bay) in Delaware (containing about 8% of the land area), Maryland (<1%), New Jersey (23%), New York (20%), and Pennsylvania (49%). Population data from the 2015 American Community Survey (Table 1.1.1, Figure 1.1.1; ACS 5-year survey, 2011-2015) indicates 8,338,000 residents live in the Basin, including 723,000 people in Delaware (9%), 6,500 in Maryland (<1%), 1,946,000 in New Jersey (23%), 120,000 in New York (1%), and 5,542,000 in Pennsylvania (67%). In 2009, nearly 3,500,000 people worked in the Delaware River Basin with 316,000 jobs in Delaware (9%), 1,100 jobs in Maryland, 823,000 jobs in New Jersey (24%), 69,800 jobs in New York (2%), and 2,271,000 jobs in Pennsylvania (65%).

Table 1.1.1 Land area, population, and employment in the Delaware River Basin by state.

State	Area mi² (km²)	Population[1] 2015	Employment[2] 2009
Delaware	965 (2,500)	723,219	316,014
Maryland	9 (23)	6,581	1,172
New Jersey	2,961 (7,669)	1,946,526	823,294
New York	2,555 (6,617)	120,055	69,858
Pennsylvania	6,280 (16,265)	5,542,318	2,271,317
Total	12,770 (33,074)	8,338,698	3,481,655

1. American Community Survey; 2. U.S. Bureau of Labor Statistics

The population of the Delaware River Basin now exceeds 8.3 million people which, if considered as a single jurisdiction, would be the 13th most populous state in the U.S. after New Jersey and Virginia. Table 1.1.2 summarizes the area, population, and employment by state and county in the Delaware River Basin. In Delaware, the Basin covers 50% of the State's area yet includes 78% of the population. The New Jersey portion of the Basin covers 40% of the State's land area and includes 22% of the population. New York State covers 5% of the State's land area and the Basin includes 0.6% of the population. The Pennsylvania part of the Basin covers just 14% of the State's area yet includes 43% of the population. The current distribution of population among the states in the Basin is shown in Figure 1.1.1. The majority of the Basin's population resides in Pennsylvania at 5,542,318 (66.5%), followed by New Jersey at about 2 million (23.3%), Delaware at 700,000 (8.7%), New York at 120,055 (1.4%), and Maryland at 6,581 (0.1%). Table 1.1.2 summarizes the total amount of people in the counties of the Delaware Bay. Figure 1.1.4 summarized population sizes per state from 200-2015. Table 1.1.3 divides population sizes by ecoregion.

1.1.3 Past Trends

Tracking changes and trends in population is critical for predicting future land cover and resource usage. These trends can help managers target critical locations for preservation and natural resource management. Population increases put higher strains on resources such as drinking water and wastewater management. Population trends provide a helpful indicator to predict future landscape changes in the Basin. Between 2000 and 2015, the population in the Delaware River Basin increased by more than 575,000 people (7%) (Table 1.1.4). Within a 5-year period (2010-2015), the Delaware River Basin increased by more than 182,000 people (1%). Over those same 5 years, population increased by 4,800 (3%) in Kent and Sussex counties, Delaware. In Philadelphia County, population grew by 30,100 people (2%). Targeting land and water management strategies in these counties would be beneficial to the Basin due to their higher risk for development and associated impacts. See Figures 1.1.5-1.18 for other representations of population changes in the Estuary and Basin.

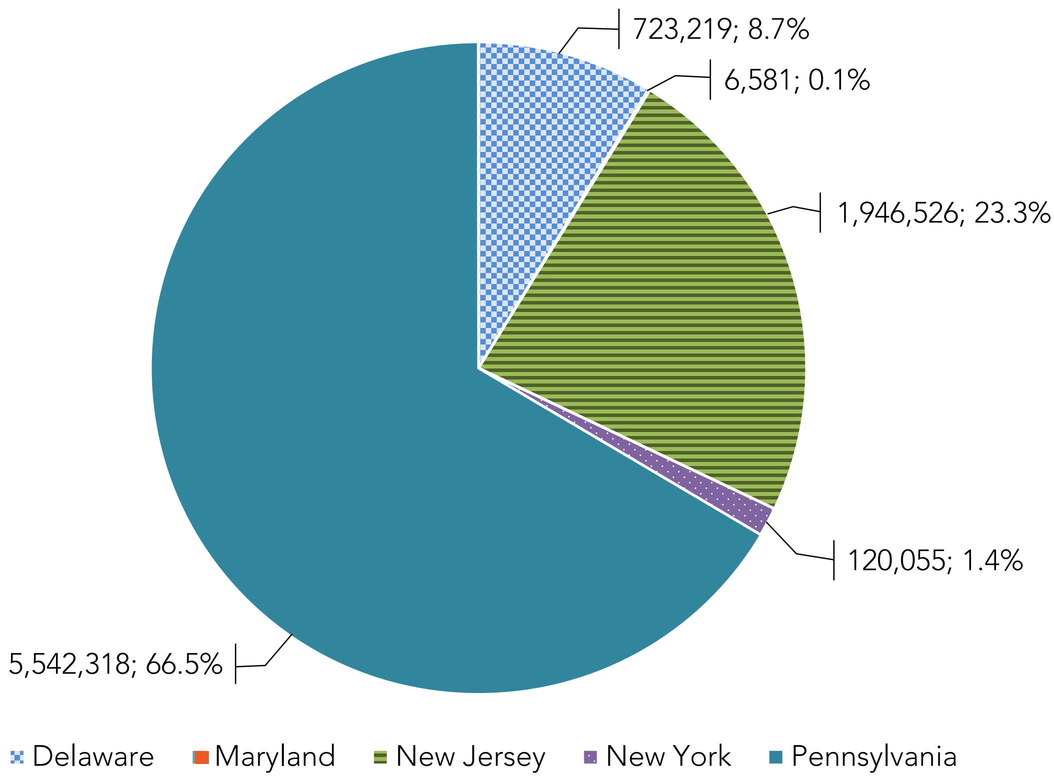

Figure 1.1.1 Population size by state (Source: American Community Survey, 2015) in the Delaware River Basin.

Table 1.1.2 Land area, population, and employment by county in the Delaware River Basin for A) Maryland, New Jersey, New York; and B) Delaware, Pennsylvania.

A. State/ County	Area[1] 2015 (mi²)	Population[2] 2015	Employment[3]
Cecil	9	6,581	1,172
Maryland	**9**	**6,581**	**1,172**
Atlantic	14	5,633	-
Burlington	498	440,646	-
Camden	122	442,534	187,758
Cape May	106	29,924	169,909
Cumberland	505	156,840	14,545
Gloucester	280	261,123	61,868
Hunterdon	173	33,246	89,183
Mercer	137	272,225	23,650
Monmouth	62	12,492	178,320
Morris	42	30,668	9,864
Ocean	77	11,769	-
Salem	354	65,274	7,495
Sussex	314	77,310	21,900
Warren	361	106,843	23,302
New Jersey	**3,045**	**1,946,526**	**35,500**
Broome	82	2,454	11,292
Chenango	3	102	-
Delaware	1,145	32,000	14,240
Greene	23	274	572
Orange	80	18,086	10,456
Schoharie	4	144	-
Sullivan	900	66,078	25,511
Ulster	156	917	7,787
New York	**2,393**	**120,055**	**69,858**

B. State/ County	Area[1] 2015 (mi²)	Population[2] 2015	Employment[3]
Kent	400	147,758	50,412
New Castle	439	528,721	252,534
Sussex	205	46,713	13,068
Delaware	**1,043**	**723,219**	**316,014**
Berks	777	400,022	150,665
Bucks	620	624,212	244,453
Carbon	389	65,180	16,730
Chester	616	464,036	212,996
Delaware	189	555,364	201,208
Lackawanna	69	6,493	4,830
Lancaster	3	988	-
Lebanon	53	17,720	2,750
Lehigh	345	350,388	166,932
Luzerne	135	22,972	8,074
Monroe	613	166,778	56,025
Montgomery	487	815,305	453,771
Northampton	377	306,094	96,536
Philadelphia	142	1,555,468	619,396
Pike	564	56,318	9,874
Schuylkill	383	84,943	27,077
Wayne	695	50,037	14,114
Pennsylvania	**6,457**	**5,542,318**	**2,271,317**
Delaware River Basin	**12,947**	**8,338,698**	**3,481,655**

1. NOAA CSC 2010; 2. American Community Survey, 5-year survey, 2011-2015;
3. U. S. Bureau of Labor Statistics 2009.

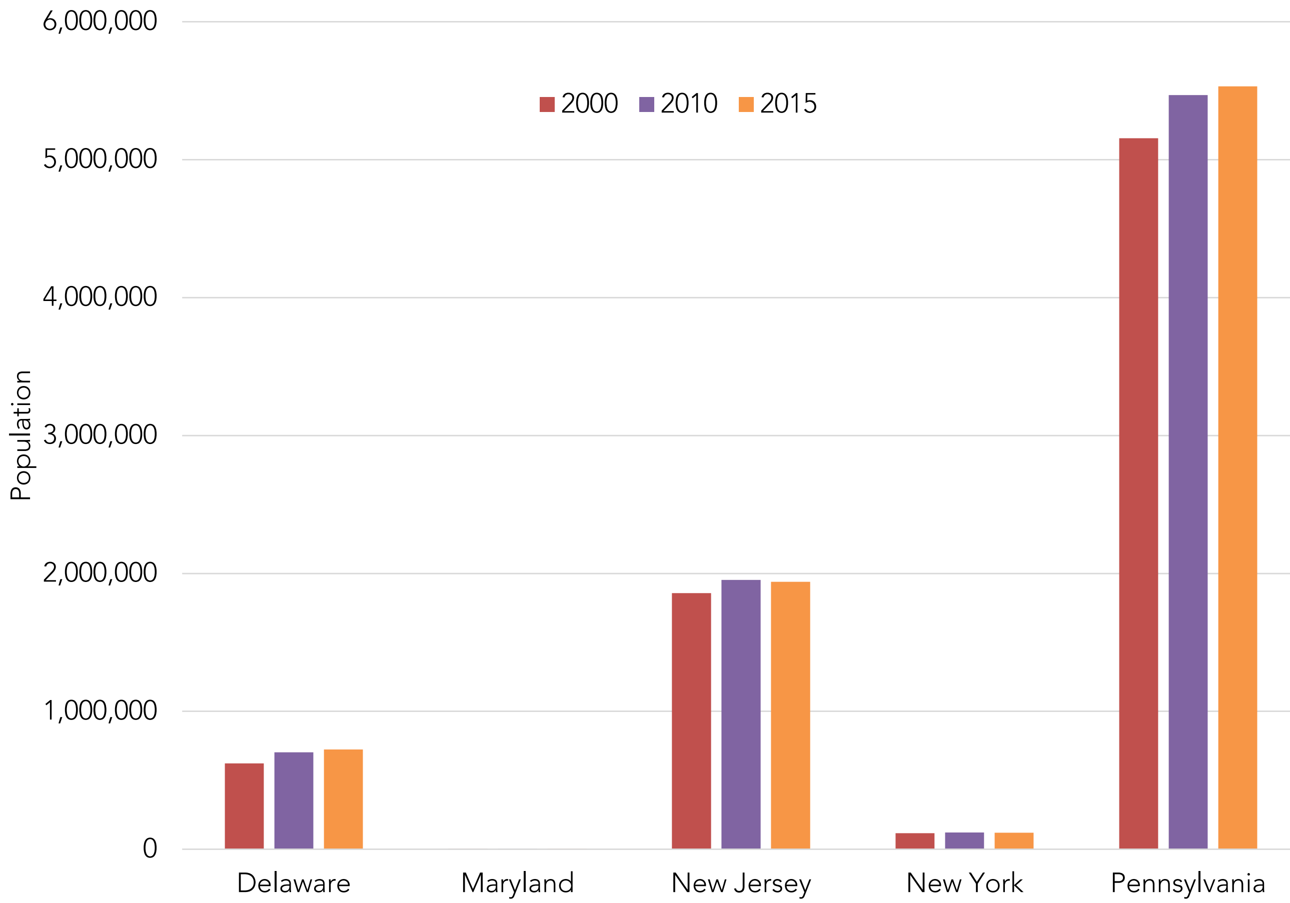

Figure 1.1.2 Population in the Delaware River Basin by state. (Source: American Community Survey, 5-year survey, 2011-2015 & U.S. Census Bureau).

Table 1.1.3 Population in Delaware River Basin regions (see Fig 0.5 for region designations), 2000-2010 (U.S. Census Bureau & American Community Survey).

Region	Population Size		
	2000	2010	2015
Upper	188,051	199,815	198,341
Central	1,191,789	1,326,600	1,319,614
Lower	6,005,528	6,288,188	6,354,257
Bayshore	376,009	439,676	449,171
Whole Basin	7,761,377	8,254,279	8,321,383

Table 1.1.4 Population size (in thousands) and population change (2000-2015) by county in the Delaware River Basin for A) Maryland, New Jersey, New York; and B) Delaware, Pennsylvania. (U. S. Census & American Community Survey)

A. State/ County	Population Size (in thousands)			Change 2000-15		Change 2010-15	
	2000	2010	2015	#	%	#	%
Cecil	5.5	6.3	6.6	1.1	20%	0.2	4%
Maryland	**5.5**	**6.3**	**6.6**	**1.1**	**20%**	**0.2**	**4%**
Atlantic	4.8	5.5	5.6	0.9	18%	0.2	3%
Burlington	413.7	439.7	440.6	26.9	7%	0.9	0%
Camden	440.7	442.2	442.5	1.9	0%	0.4	0%
Cape May	31.8	30.8	29.9	-1.8	-6%	-0.9	-3%
Cumberland	146.8	156.9	156.8	10.1	7%	0.1	0%
Gloucester	231.9	258.3	261.1	29.2	13%	2.8	1%
Hunterdon	32.6	35.1	33.2	0.7	2%	-1.9	-5%
Mercer	259.1	269.3	272.2	13.1	5%	2.9	1%
Monmouth	9.9	12.4	12.5	2.6	27%	0.1	1%
Morris	27	30.6	30.7	3.6	13%	0.1	0%
Ocean	10.2	11.7	11.8	1.5	15%	0.0	0%
Salem	64.6	66	65.3	0.7	1%	-0.7	-1%
Sussex	76.4	78.9	77.3	0.9	1%	-1.6	-2%
Warren	101.8	108.6	106.8	5.0	5%	-1.7	-2%
New Jersey	**1,851.2**	**1,946**	**1,946.5**	**95.3**	**5%**	**0.6**	**0%**
Broome	2.4	2.3	2.5	0.1	4%	0.2	7%
Chenango	0.1	0.1	0.1	0.0	-15%	0.0	-1%
Delaware	32.4	32.9	32	-0.4	-1%	-0.9	-3%
Greene	0.2	0.2	0.3	0.1	22%	0.0	16%
Orange	17.7	18.3	18.1	0.4	2%	-0.2	-1%
Schoharie	0.1	0.1	0.1	0.0	16%	0.0	7%
Sullivan	63.4	66.3	66.1	2.6	4%	-0.3	0%
Ulster	1.0	0.9	0.9	-0.1	-12%	0.0	-3%
New York	**117.5**	**121.2**	**120.1**	**2.6**	**2%**	**1.1**	**-1%**

B. State/ County	Population Size (in thousands)			Change 2000-15		Change 2010-15	
	2000	2010	2015	#	%	#	%
Kent	107.9	141.3	147.8	39.9	37%	6.4	5%
New Castle	486.3	519.1	528.7	42.4	9%	9.6	2%
Sussex	29.6	43.5	46.7	17.1	58%	3.2	7%
Delaware	**623.8**	**704**	**723.2**	**99.4**	**16%**	**19.3**	**3%**
Berks	361.4	397.6	400.0	38.7	11%	2.4	1%
Bucks	593.9	622.2	624.2	30.3	5%	2.1	0%
Carbon	59.0	66.0	65.2	6.2	10%	-0.8	-1%
Chester	396.8	453.8	464.0	67.2	17%	10.3	2%
Delaware	544.6	553.2	555.4	10.8	2%	2.2	0%
Lackawanna	5.6	6.4	6.5	0.9	16%	0.1	1%
Lancaster	0.7	1.1	1.0	0.3	34%	-0.1	-9%
Lebanon	15.0	17.0	17.7	2.7	18%	0.7	4%
Lehigh	305.7	343.1	350.4	44.7	15%	7.3	2%
Luzerne	21.4	23.2	23.0	1.6	7%	-0.2	-1%
Monroe	137.6	169.2	166.8	29.2	21%	-2.4	-1%
Montgomery	751.3	802.3	815.3	64.0	9%	13.0	2%
Northampton	273.5	304.0	306.1	32.5	12%	2.1	1%
Philadelphia	1,518.2	1,525.4	1,555.5	37.2	2%	30.1	2%
Pike	46.5	57.2	56.3	9.8	21%	-0.9	-2%
Schuylkill	87.3	85.9	84.9	-2.4	-3%	-1.0	-1%
Wayne	46.6	51.2	50.0	-3.4	7%	-1.1	-2%
Pennsylvania	**5,165.1**	**5,478.6**	**5,542.3**	**377.2**	**7%**	**63.7**	**1%**
Delaware River Basin	Population (in millions)			2000-15		2010-15	
	2000	2010	2015	#	%	#	%
	5.17	5.48	5.54	0.38	7%	0.6	1%

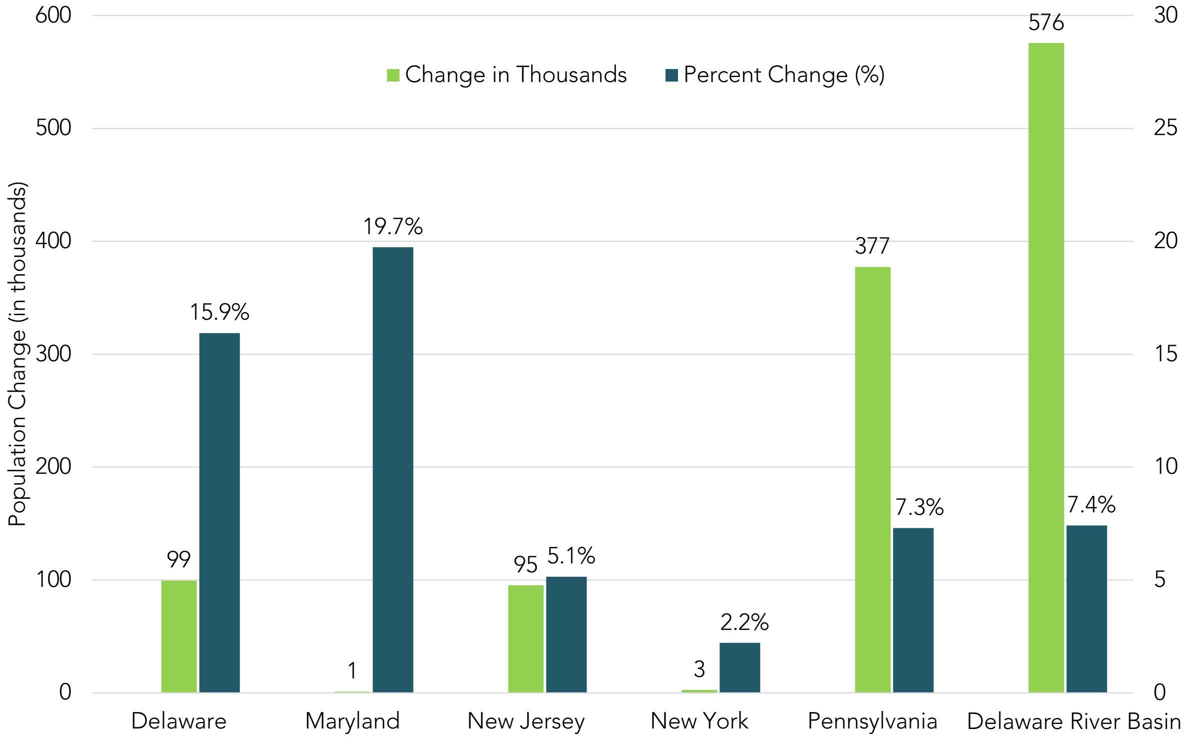

Figure 1.1.3 Population change in the Delaware River Basin, 2000-2015 (U.S. Census Bureau & American Community Survey).

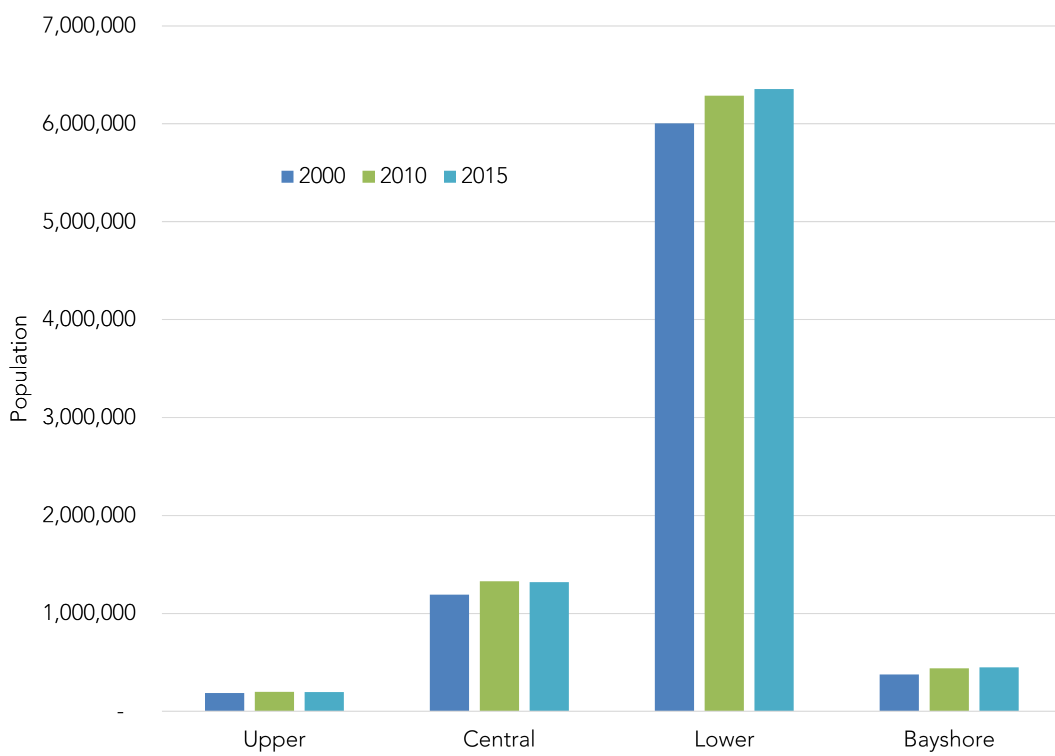

Figure 1.1.4 Population in the Delaware River Basin by Region (U.S. Census Bureau & American Community Service).

Table 1.1.5 Sub-Watersheds in the Delaware River Basin (American Community Service & U.S. Census)

Watershed		Population Size			Population Change			
					2000-2015		2010-2015	
Code	Description	2000	2010	2015	#	%	#	%
LE1	Brandywine/Christina	424,694	430,615	434,779	5,921	1.4%	4164	1%
LE2	C&D Canal	57,613	83,428	88,683	25,815	44.8%	5255	6%
DB1	Delaware Bay	141,472	189,891	199,651	48,419	34.2%	9760	5%
	Delaware	**623,779**	**703,934**	**723,113**	**80,155**	**12.8%**	**19,179**	**3%**
LE1	Maryland	5,496	6,339	6,581	843	15.3%	242	4%
	Maryland	**5,496**	**6,339**	**6,581**	**843**	**15.3%**	**242**	**4%**
UC2	NJ Highlands	218,808	232,511	219,868	13,703	6.3%	-12643	-6%
LC1	Del. Rvr. abv Trenton	58,146	57,828	58,975	-318	-0.5%	1146	2%
UE2	New Jersey Coastal Plain	1,292,170	1,353,930	1,351,421	61,760	4.8%	-2509	-0.2%
LE3	Salem River	54,518	59,457	59,670	4,938	9.1%	214	0.4%
DB2	Delaware Bay	234,537	249,785	249,521	15,248	6.5%	-264	-0.1%
	New Jersey	**1,858,179**	**1,953,511**	**1,939,455**	**95,331**	**5.1%**	**-14,056**	**-1%**
EW1	East Branch Del. Rvr.	22,155	22,791	22,755	637	2.9%	-36	-0.2%
EW2	West Branch Del. Rvr.	19,222	18,789	17,848	-433	-2.3%	-941	-5%
EW3	Del. Rvr. abv Pt. Jervis	11,188	11,298	11,339	110	1.0%	41	0.4%
NM1	Neversink R.	64,982	68,352	68,114	3,370	5.2%	-239	-0.4%
	New York	**117,546**	**121,230**	**120,055**	**3,684**	**3.1%**	**-1,175**	**-1%**
EW3	Del. Rvr. abv Pt. Jervis	8,633	9,030	8,537	398	4.6%	-493	-6%
NM1	Neversink Rvr.	12,136	13,053	12,984	917	7.6%	-69	-1%
LW1	Lackawaxen Rvr	49,736	56,502	56,766	6,765	13.6%	264	0.5%
UC1	Pocono Mt.	208,525	251,121	249,475	42,596	20.4%	-1646	-1%
LV1	Lehigh River abv Lehighton	37,667	48,120	45,569	10,454	27.8%	-2551	-6%
LV2	Lehigh River abv Jim Thorpe	88,387	99,152	97,784	10,765	12.2%	-1368	-1%
LV3	Lehigh River abv Bethlehem	478,573	529,935	539,139	51,362	10.7%	9204	2%
LC1	Del. Rvr. abv Trenton	101,683	107,933	108,803	6,250	6.1%	870	1%
SV1	Schuylkill abv Reading	88,741	87,033	85,965	-1,708	-1.9%	-1068	-1%
SV2	Schuylkill abv Valley Forge	321,337	354,874	357,158	33,537	10.4%	2284	1%
SV3	Schuylkill abv Philadelphia	952,451	1,010,730	1,029,817	58,279	6.1%	19087	2%
UE1	Penna Fall Line	2,573,270	2,625,750	2,657,510	52,480	2.0%	31760	1%
LE1	Brandywine/Christina	235,237	276,033	282,673	40,796	17.3%	6640	2%
	Pennsylvania	**5,156,376**	**5,469,266**	**5,532,180**	**312,890**	**6.1%**	**62,914**	**1%**
	Delaware River Basin	**7,755,881**	**8,247,941**	**8,321,282**	**492,060**	**6.3%**	**67,104**	**1%**

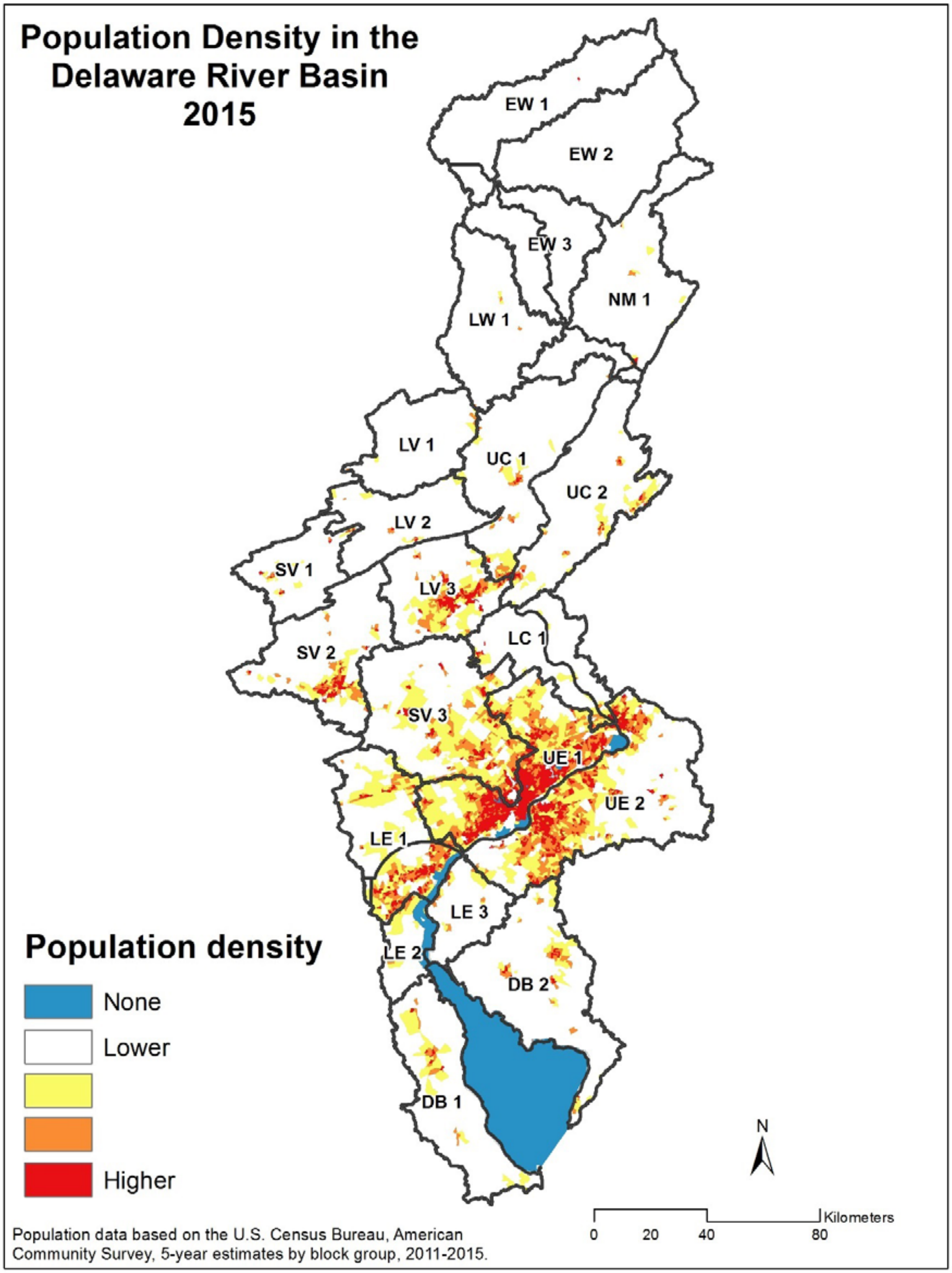

Figure 1.1.5 Population density in the Delaware River Basin, 2015 (U.S. Census Bureau). Reference Fig 0.7 for abbreviation legend.

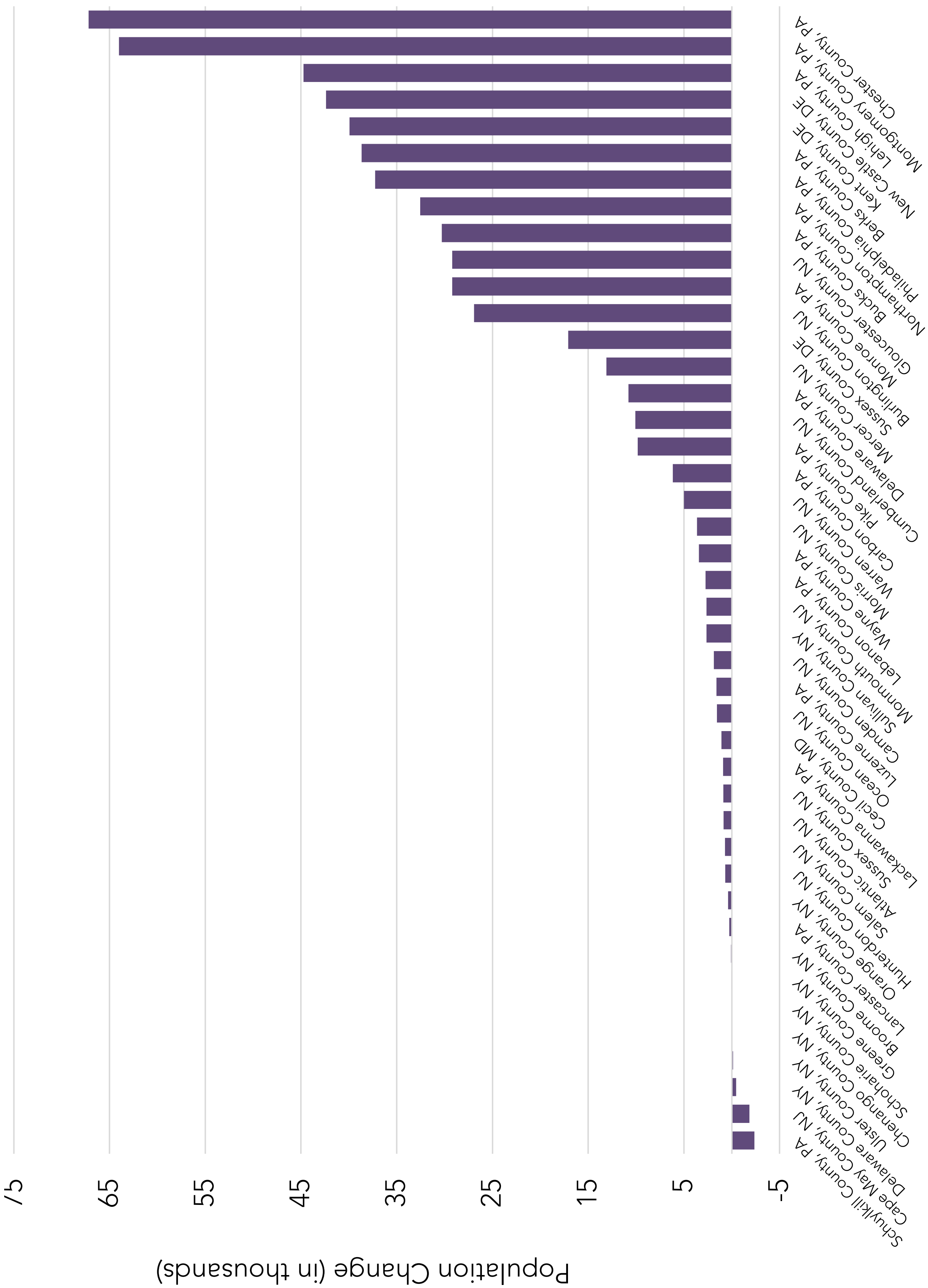

Figure 1.1.6 Population change in Delaware River Basin counties, 2000-2015 (U.S. Census Bureau & American Community Survey)

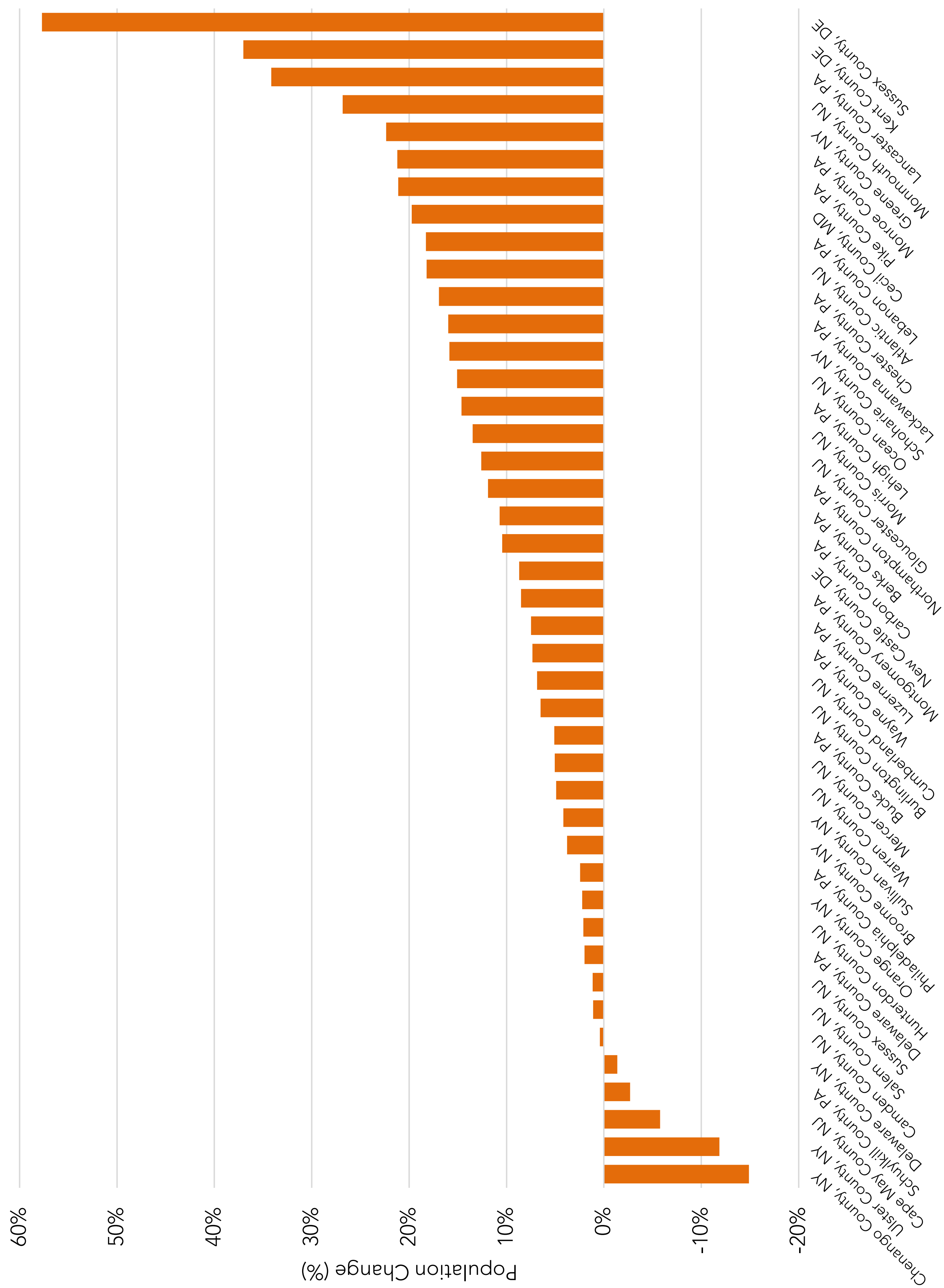

Figure 1.1.7 Percent population change in Delaware River Basin counties, 2000-2015 (U.S. Census Bureau & American Community Survey)

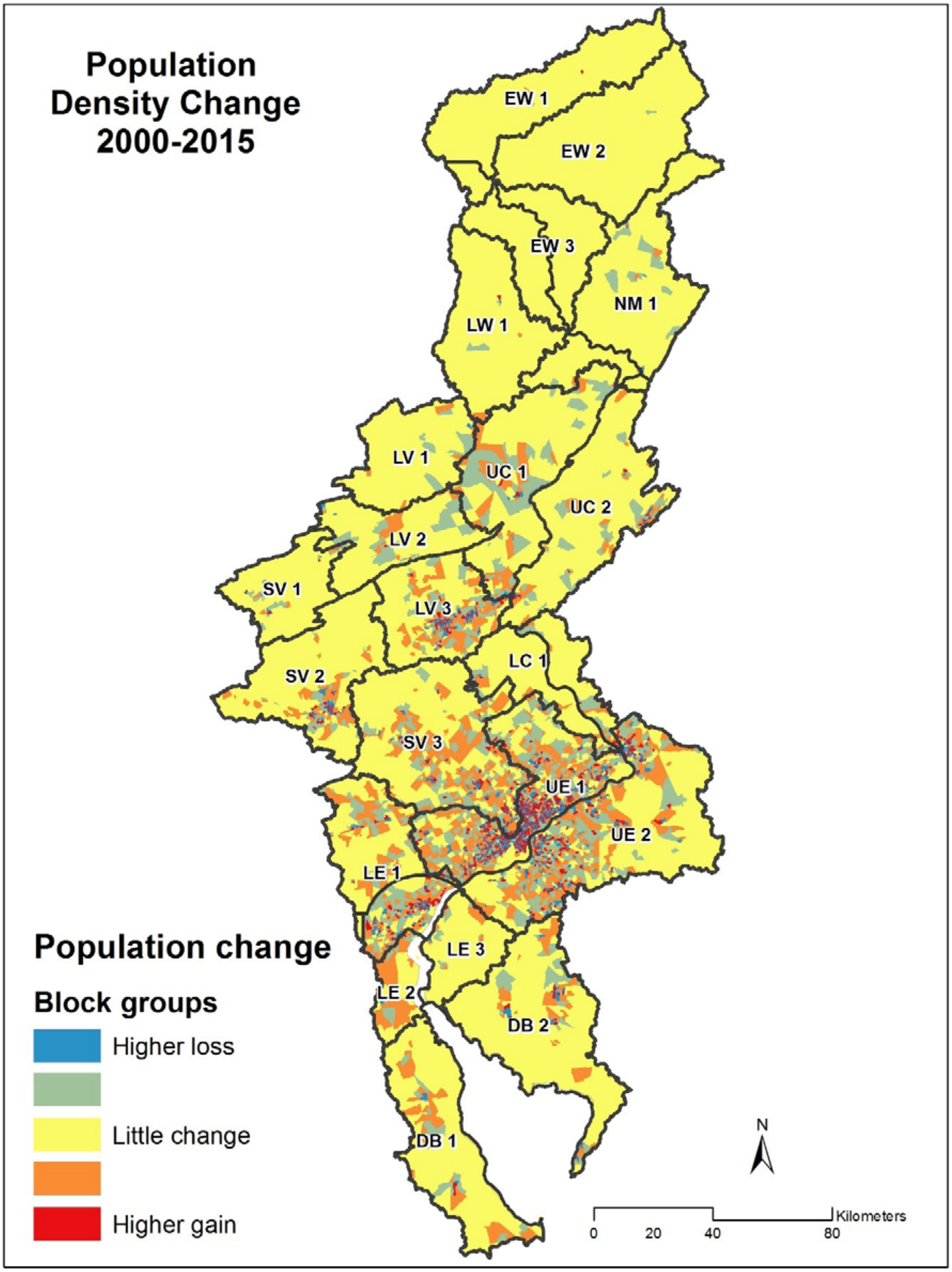

Figure 1.1.8 Change in population density in the Delaware River Basin, 2000-2015. Reference Fig 0.7 for abbreviation legend.

1.1.4 Future Predictions

The population of Delaware River Basin counties is projected to grow by a half million people every decade through 2030. Most gains as a percentage are likely to occur in Kent and Sussex Counties, Delaware; and Chester, Monroe and Montgomery Counties, Pennsylvania. Cape May and Salem County, New Jersey and Philadelphia county, PA are projected to experience a loss in population by 2030. Understanding these projected trends can help planners and resource managers prepare for expected changes and prioritize strategies to deal with them. Planning and infrastructure resources should be directed to areas such as Bayshore counties (e.g., Kent and Sussex County, Delaware), or rapidly developing areas in the highly forested Central Region, to help mitigate the impacts population change can have on ecologically sensitive landscapes. See Figure 1.1.9 for the spatial distributions of population changes.

1.1.5 Actions and Needs

As population continues to grow in the Delaware River Basin, watershed managers should prepare for the challenges these changes will entail. Targeted efforts to mitigate the impacts of development are recommended in order to plan for challenges to natural resources management, including increased drinking water demand and wastewater treatment challenges, increased stormwater management concerns, and overall water quality and watershed health. Continued monitoring of these trends is recommended to help predict future impacts on land use, as well as water quality. Strategies such as green infrastructure and landscape buffers can be targeted in highly populated areas to help offset the impacts of increased imperviousness and stormwater runoff. Regional master plans should continue to factor in population change and projections in order to plan for expected increases in demand for limited resources.

1.1.6 Summary

Census data indicate 8,338,698 residents live in the Basin. Over a 15-year period (2000-2015), the population in the Delaware River Basin increased by 6.3% (492,060 individuals). The most significant percent gains were found in Sussex County, Delaware (58% gain) and Kent County, Delaware (37% gain). The most significant losses were found in Chenango County, New Jersey (15% loss) and Ulster County, NJ (12% loss). Overall, between 2000 and 2015, population in Delaware rose by 12.8%, in Maryland by 15.3%, in New Jersey by 5.1%, in New York by 3.1%, and in Pennsylvania by 6.1%. Future projections indicate that the Delaware River Basin will continue to grow. Absolute numbers of people will increase in the counties in and around Philadelphia, while by percentage, the counties of the Central and Bayshore Regions will see the highest growth.

Suggested Citation for this Chapter

Somers, K., G. Kauffman, A. Homsey. 2017. "Chapter 1.1 - Population" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 18-29.

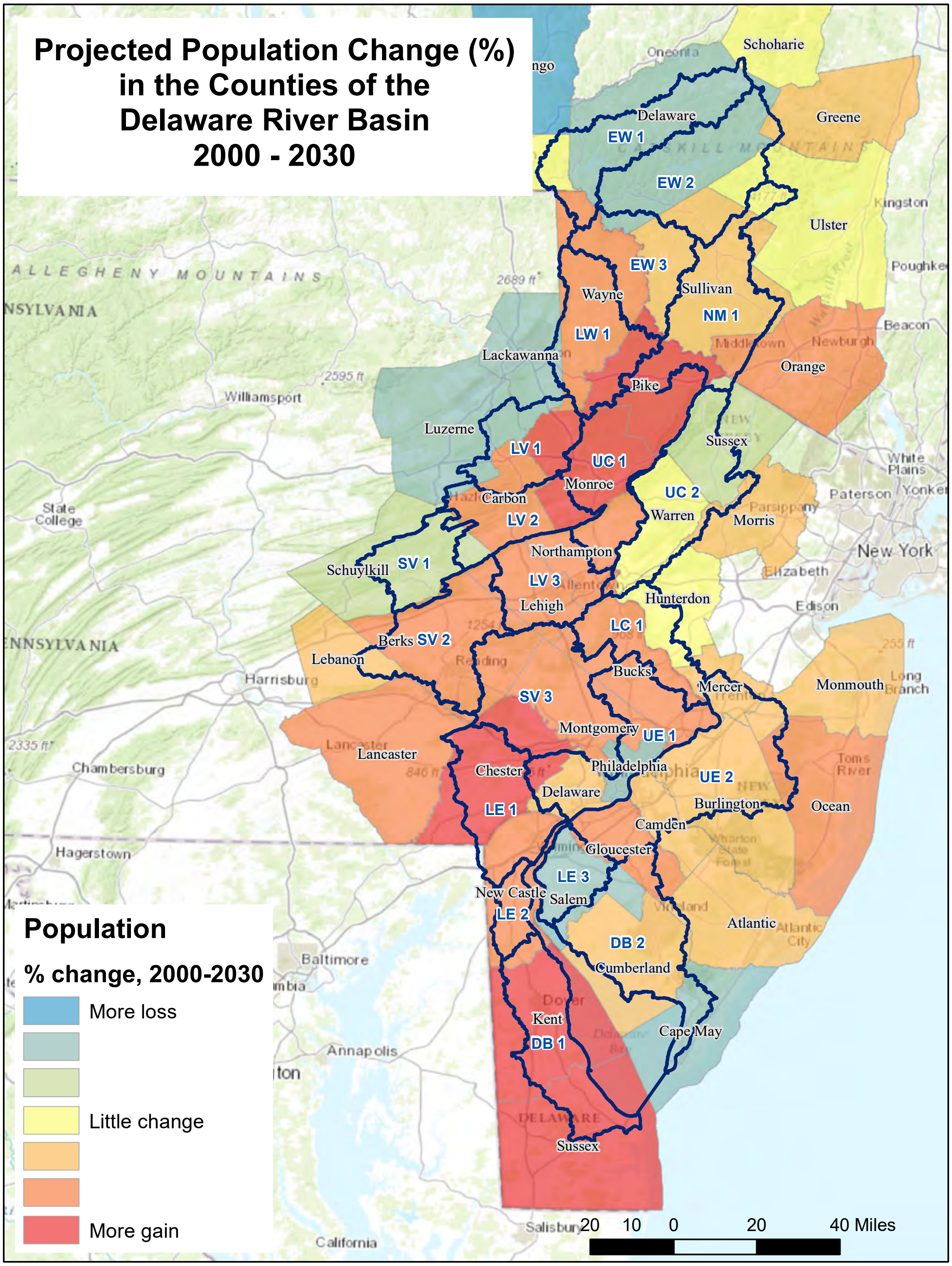

Figure 1.1.9 Population projections (2000-2030) for the Delaware River Basin. These are numbers based on counties that fall within the Delaware River Basin, but include areas of those counties that may fall outside Basin Boundaries. Reference Fig 0.7 for abbreviation legend.

1.2 Current Land Cover

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1.2.1 Introduction

Assessment of land use/land cover within the Basin is an important component of determining both the current status and past or future trends within a watershed. For the current analysis, land cover is the more important consideration since it bears directly on the effects of the landscape and on the health of the watersheds of the Delaware Estuary and Basin. Land use changes in the Basin are an indicator of human impacts and it is imperative to understand the dynamic relationship between human use of the watershed and its overall health.

A particular challenge in assessing the land cover types across a region as large as the Delaware River Basin is assuring that data are consistent across the area (in particular across multiple state lines), and across time (i.e., for determining land cover changes). In the 2012 Technical Report for the Delaware Estuary and Basin (TREB 2012), analysis of available data source for land cover types determined that using data generated by the NOAA Coastal Services Center (CSC) through their Coastal Change and Analysis Program (C-CAP) enabled the most robust and reliable analysis. The C-CAP data are compiled from satellite imagery at 30 meter ground resolution, as is the USGS National Land Cover Dataset (NLCD). As described in the TREB 2012, this latter dataset does not have the frequency (10 years re-visit time versus approximately 5 years for the C-CAP data) nor the consistency across epochs (time periods) required to make change comparisons. Using state-specific vector-based data derived from aerial photography had similar drawbacks, with the additional problem of incompatible classification methodologies and unsynchronized dates.

While the original parameters of the C-CAP program did not include the entire Basin, in the course of compiling the 2008 State of the Basin report, this data gap was addressed. The Delaware River Basin Commission (DRBC) requested that the NOAA CSC expand the area of delineation beyond the traditional 200 mile inland limit to include areas of the Basin not previously included. The CSC complied with the request, resulting in comprehensive coverage of the entire Basin.

It should be noted that, based on assessment of the datasets by the University of Delaware Water Resources Center, it has been determined that land cover data from previous dates (i.e., prior to the latest 2010 data) have been reclassified, requiring a re-calculation of the land cover statistics for the Basin for all prior years: 1996, 2001, 2006. Differences in the land cover values between previous reports and the current report are explained by the updated values.

The DRBC divided the Delaware River Basin into 10 watersheds distinguished by major tributaries or physiography (Table 1.2.1). These ten watersheds have been further subdivided into a total of 21 sub-watersheds. Larger-scale divisions include four regions (Upper Region, Central Region, Lower Region, and Bayshore), and a distinction between the Delaware Estuary (watersheds of the tidal portion of the Basin) and nontidal watersheds. Figure 1.2.1 shows the percentage of land area within each of the four regions of the Delaware River Basin.

Table 1.2.1 Basin assessment units and reporting hierarchy. Regions are further divided into watersheds (e.g. Lackawaxen, Upper Estuary 1 or 2).

Basin										
Nontidal						Estuary				
Upper Region			Central Region			Lower Region			Bayshore Region
East-West 1, 2, 3	Lacka-waxen	Neversink-Mongaup	Upper Central 1,2	Lehigh Valley 1,2,3	Lower Central	Schuylkill Valley 1,2,3	Upper Estuary 1,2	Lower Estuary 1,2,3	Bayshore 1,2

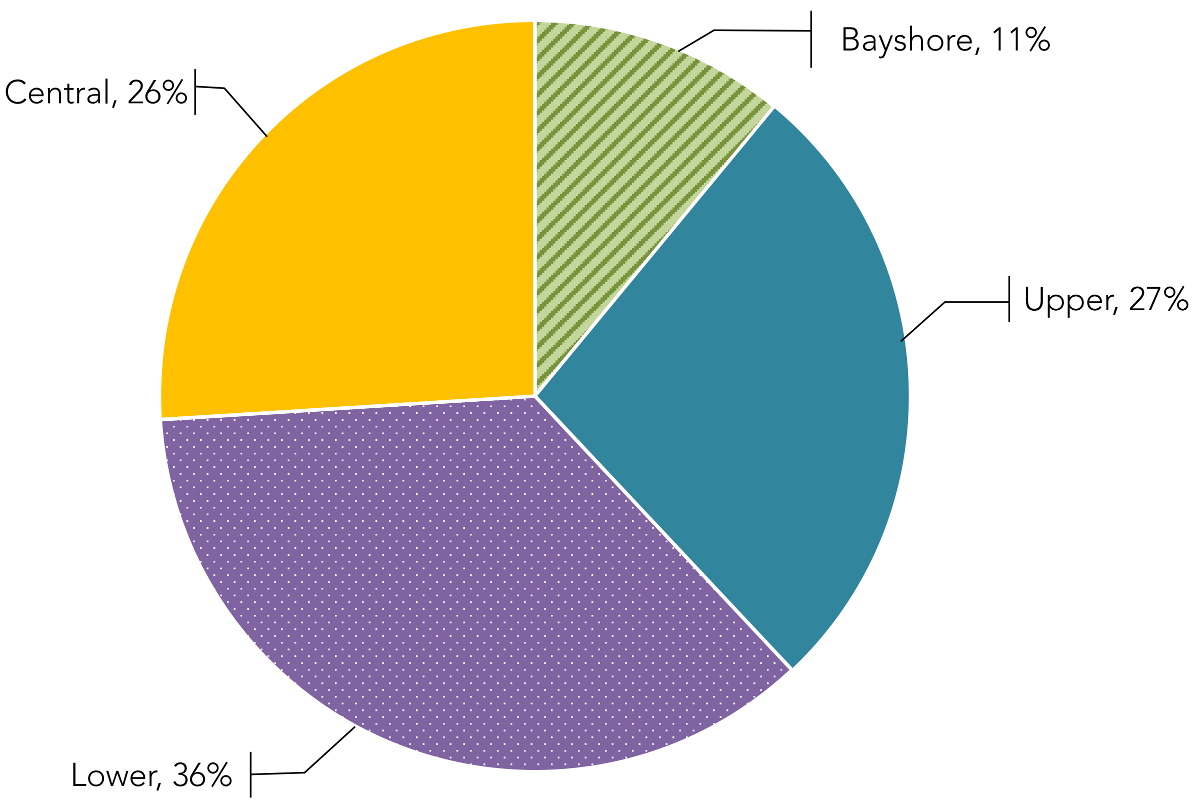

Figure 1.2.1 Percent area of the Basin occupied by each Region.

1.2.2 Description of Indicator

Land use and land cover are typical methods used to characterize landscapes. Understanding how humans use the land and what types of land cover occur can help planners and managers assess characteristics such as economic activity, population patterns, infrastructure needs, and watershed health. The quality of the habitats within the watersheds of the Delaware River Basin, and the quality and quantity of the waters of the Basin are all important factors that result largely from the way the land is being used.

NOAA CSC's C-CAP data defines 21 classes of land cover. For this analysis, these categories were consolidated into six broad land cover categories: Developed, Agriculture, Forest, Wetlands, Open Water, and Other (Table 1.2.2).

Table 1.2.2 Descriptions of land cover categories from CSC C-CAP data.

Developed	Agriculture	Forest	Wetlands	Open Water	Other
Low Intensity	Cultivated Lands	Deciduous	Palustrine and Estuarine Emergent	Open Water	Unconsolidated Shore
Medium Intensity	Pasture	Evergreen	Shrub-Scrub	Palustrine Aquatic Beds	Transitional Land
High Intensity	Grassland	Mixed Forest	Forested		Other
Open Space	Shrub-Scrub				

Developed land is generally associated with lower quality habitat and lower water quality values than more natural types of land cover. Additionally, water quantity is affected by development. Highly developed areas tend to be more impervious to infiltration (see Chapter 1.4 - Impervious Cover), and can therefore increase runoff, leading to more "flashy" streams and increased pollutant loads, particularly of toxics, metals, and other byproducts of human activity. Additionally, higher levels of development tend to decrease the base (i.e., groundwater-influenced) flows in streams, impacting water supplies downstream. Human-related effects such as increased road density, increased waste production, and increased water usage also result from development.

Agricultural land cover, making up nearly a quarter of the Basin in 2010, can have widely variable effects on the heath of watersheds and on water quality and quantity. Variables include type of crop, intensity of farming, presence of animals, and conservation practices. Overall, it is expected that in areas of agriculture (and downstream of them) there will be higher levels of nutrients (nitrogen levels tend to be elevated in the groundwater as well as the surface water), bacteria, and sediment.

Forest cover is associated with pre-development conditions of water quality and hydrology. Forests cycle nutrients and carbon dioxide, capture rainfall and inhibit erosion, and play an important role in water quality, quantity, and habitat provision for aquatic and terrestrial wildlife. Forested watersheds are often used to define natural reference conditions for streams. Mature forest is considered to be a benchmark for defining high-quality watersheds.

Wetlands, both freshwater and tidal, are similar to forests in their association with clean and healthy watersheds. They provide a wide variety of ecosystem services, including water purification, habitat provision, flood protection, pollution reduction, recreation, as well as sea-level rise and storm-surge amelioration.

Land cover as an indicator of watershed health is most effectively considered in combination with other factors such as population and impervious cover. Population and demographic trends can often be used to predict expected changes to land cover (and thus the expected effects on watershed health), while impervious cover is directly related to development as is discussed in Chapter 1.4.

Land cover as considered here can be a helpful indicator of overall health of the Basin at the landscape scale. It is always helpful when looking at smaller areas for watershed planning purposes to analyze ground conditions through more thorough research, including compilation of ground-verified data.

1.2.3 Present Status

The Delaware River Basin The Delaware River Basin comprises approximately 12,866 square miles (33,323 km^2) within Delaware, New Jersey, New York, Pennsylvania, and Maryland. Over half (53%) falls within the nontidal watersheds of the Basin. The remainder forms the Delaware Estuary (i.e., the watersheds of the tidal portion of the Basin). The Delaware Bay itself is in the lower portion of the Estuary, and covers 747 mi^2 (1,936 km^2), resulting in a total area of 13,614 square miles (35,268 km^2) for the Basin (including the Delaware Bay) (Tables 1.2.4 and 1.2.5). With the Bay included, more than half (50.2%) of the Basin is part of the Delaware Estuary (and under the stewardship of the National Estuary Program). All land cover analysis has excluded the Bay from consideration. Figure 1.2.2 shows the land cover of the Delaware River Basin.

Figure 1.2.3 shows the percentage of each land cover type for the Basin. Forest is the predominant land cover, representing approximately 48% of the total land area. Agriculture makes up nearly one quarter of the area (24%), developed land makes up 16%, wetlands 9%, and water or other land cover types comprise approximately 2% of the Basin area. Table 1.2.3 presents the land cover summary by region within the Delaware River Basin.

Land cover types are not distributed equally across the Delaware River Basin, but vary greatly based on location within the region. The Upper and Central Regions are dominated by forest cover and account for

Table 1.2.3 Current extent of land cover types in each region of the Basin (mi^2).

Region	Land Cover Category						
	Developed	Agriculture	Forest	Wetland	Open Water	Other	Total
Upper	61	428	2,747	120	78	8	3,442
Central	405	761	1,868	227	62	14	3,337
Lower	1,468	1,411	1,259	410	82	23	4,653
Bayshore	162	531	221	445	51	8	1,420
% of Basin	16.3%	24.4%	47.4%	9.4%	2.1%	0.4%	100%

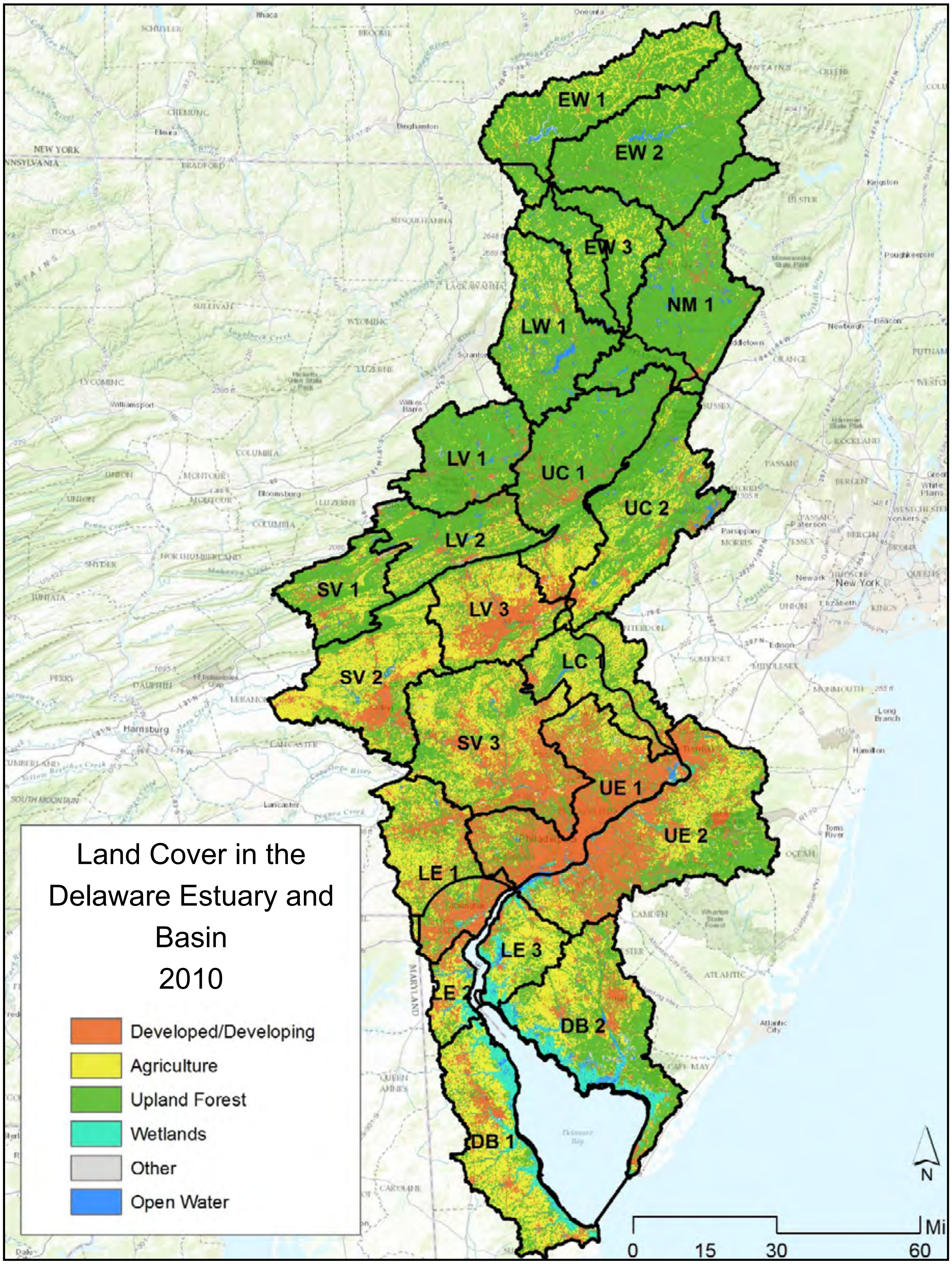

Figure 1.2.2 Distributions of land cover types across the Delaware Estuary and Basin. Reference Fig 0.6 for abbreviation legend.

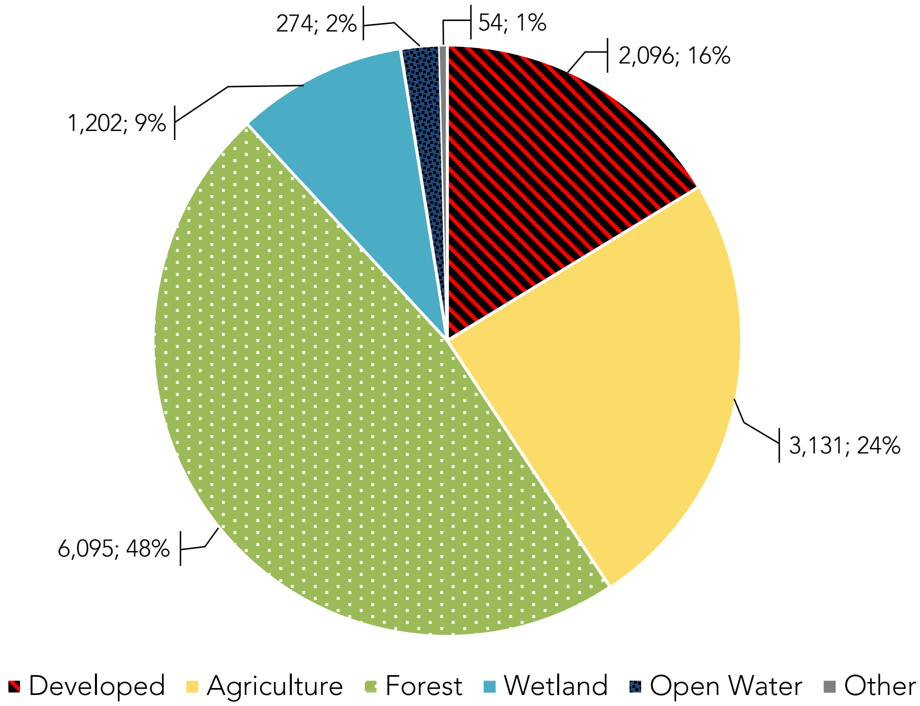

Figure 1.2.3 Coverage of each land category in the Basin. Data labels are square miles, followed by percentage of Basin area.

Table 1.2.4 Watershed Land Areas within the Nontidal Region of the Basin.

Region	Upper			Central		
Watersheds	East-West	Lackawaxen	Neversink-Mongaup	Lehigh Valley	Upper Central	Lower Central
Area	2030 mi²	598 mi²	816 mi²	1362 mi²	1524 mi²	454 mi²
	5259 km²	1547 km²	2112 km²	3526 km²	3948 km²	1175 km²
% of Region	59 %	17 %	24 %	41 %	46 %	14 %
% of Basin	27 %			26 %		

Table 1.2.5 Watershed Land Areas within the Estuary Region of the Basin.

Region	Lower			Bayshore	
Watersheds	Schuylkill Valley	Upper Estuary	Lower Estuary	Delaware	New Jersey
Area	1892 mi²	1745 mi²	1021 mi²	634 mi²	790 mi²
	4897 km²	4518 km²	2644 km²	1642 km²	2044 km²
% of Region	41 %	37 %	22 %	45 %	55 %
% of Basin	36 %			11 %	
% of Estuary	77 %			23 %	

about three-quarters of the Basin's forested area. The Lower Region is the most heavily developed and populated area of the Basin, as reflected in the predominance of human use (development, 32%; agriculture, 30%); indeed, nearly three-quarters of all development within the Basin is found in the watersheds of the Lower Region, which accounts for the highly impacted water quality found there. Wetlands occur throughout the Basin, but are predominantly found in the Lower Region and Bayshore (see Chapter 5 for a full discussion of wetlands).

Similarly, watersheds within regions exhibit notable variation in land cover and use. Figure 1.2.4 illustrates the variation in the landscape characteristics of watershed from north (East-West Branch, left side of the figure) to south (Delaware Bay, right side of the figure). Forest predominates in the northernmost region, and represents the largest portion of land cover through the Upper Central Region. South of the Upper Central Region, the influence of forest is much lower, with agriculture and development predominating. Development is most significant in the Upper Estuary, containing Philadelphia, and notable in the Schuylkill Valley and Lower Estuary, in the Philadelphia metropolitan area. Tidal regions to the south contain the most significant areas of wetlands, particularly the Delaware Bay region (where tidal marsh is a dominant land cover type).

The Delaware Estuary The Delaware Estuary comprises the four watersheds of the southern portion of the Delaware River Basin (Schuylkill Valley, Upper Estuary, Lower Estuary, and Delaware Bay). In total, the Estuary covers nearly 6,100 square miles, or nearly half (47%) of the Delaware River Basin. Table 1.2.6 summarizes the area, in square miles, of the sub-basins for the land cover types in the Delaware Estuary. Figure 1.2.5 presents the proportion of land uses within the Estuary.

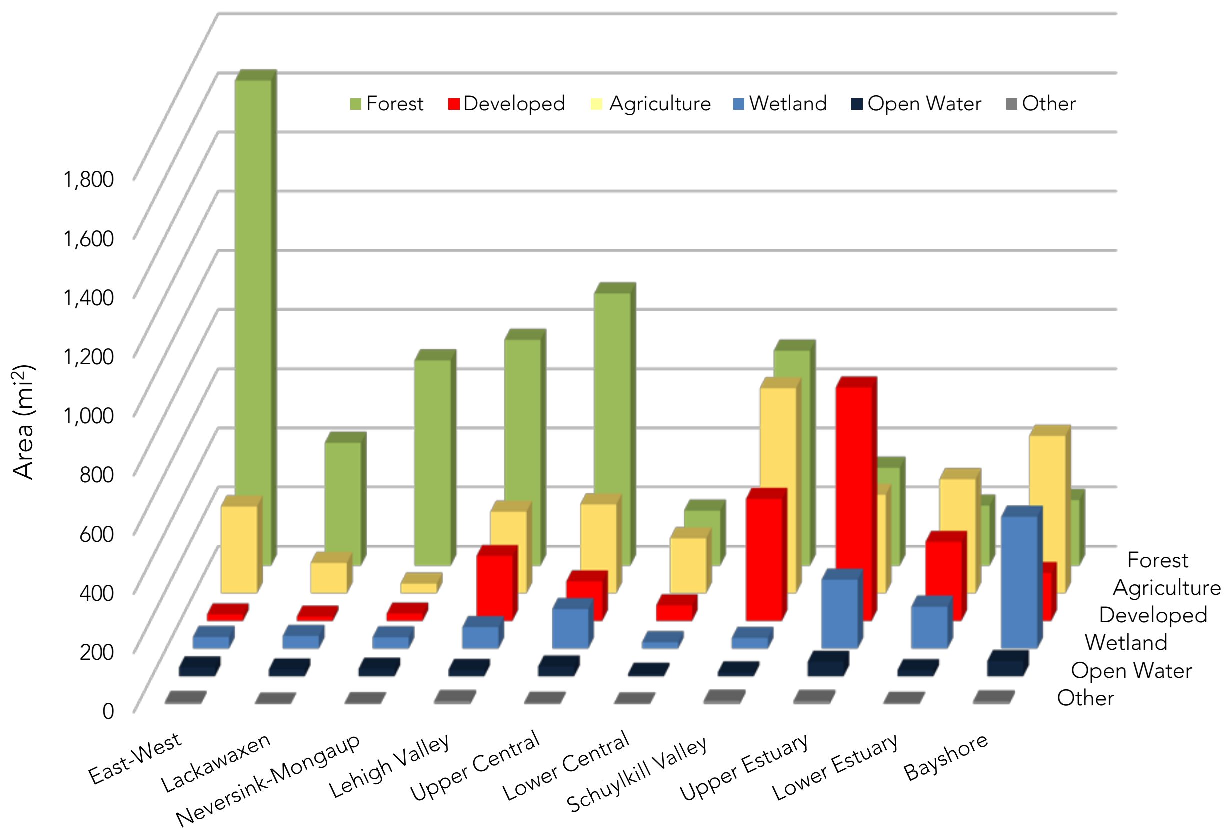

Figure 1.2.4 Area of each land cover category across the watersheds in the Basin.

Table 1.2.6 Land cover for Estuary regions in the Basin for (A) the four sub-basins within the Estuary and (B) the Estuary total area within the Whole Basin. Area values are square miles with percentages in parentheses.

A. Area of Sub-Basin	CSC Land Cover Category						Area of Estuary
	Developed	Agriculture	Forest	Wetland	Open Water	Other	
Schuylkill Valley	412 (22%)	693 (37%)	726 (38%)	36 (2%)	13 (1%)	10 (1%)	1,890 (31%)
Upper Estuary	789 (45%)	333 (19%)	330 (19%)	233 (13%)	49 (3%)	10 (1%)	1,743 (29%)
Lower Estuary	267 (26%)	385 (38%)	202 (20%)	142 (14%)	20 (2%)	3 (0%)	1,020 (17%)
Delaware Bay	162 (11%)	531 (37%)	221 (16%)	445 (31%)	51 (4%)	8 (1%)	1,420 (10%)

B. Area of Estuary	CSC Land Cover Category						Area of Whole Basin
	Developed	Agriculture	Forest	Wetland	Open Water	Other	
Estuary	1,630 (27%)	1,942 (32%)	1,480 (24%)	855 (14%)	134 (2%)	32 (1%)	6,073 (47%)

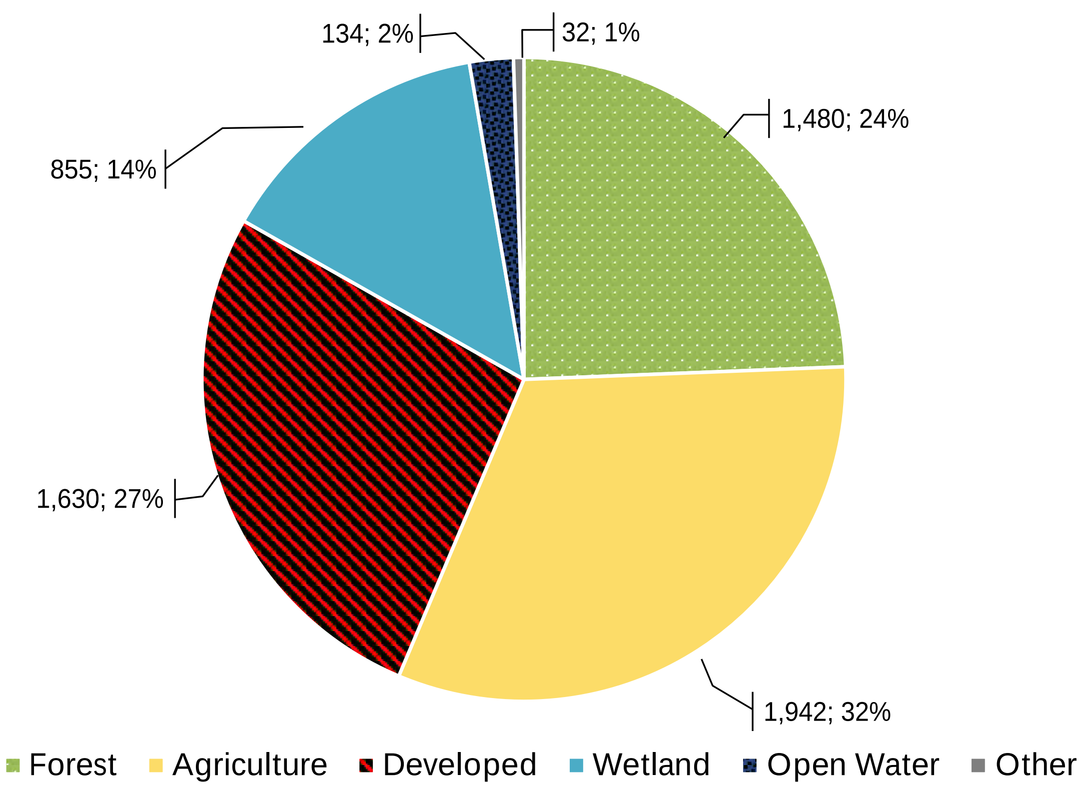

Figure 1.2.5 Coverage of each land category in the Estuary. Data labels are square miles; percentage of the Estuary and Basin area.

Though it makes up just under half the total land area of the Delaware River, the Delaware Estuary contains approximately 78% of all the development, 62% of the agriculture, and 71% of wetlands within the Basin, while only containing 24% of the forest land. See Figure 1.2.3, page 36, for the percentages of land cover types as a proportion of the entire Delaware River Basin.

The preponderance of human influence on the land, along with the extensive tidal wetlands mean that the Delaware Estuary portion of the Basin is particularly prone to negative impacts such as forest fragmentation, water quality degradation, and potential inundation from sea level rise. Development pressure and the myriad competing interests make the watersheds of the region dynamic drivers of economic activity but also render them vulnerable to degradation.

1.2.4 Past Trends

Land cover and land use are constantly evolving, resulting in variable effects over time. The ability to obtain a synoptic view of the land is relatively new, and has become increasingly possible since the advent of satellite remote sensing of the environment in the last 60 years or so. The changes and potential impacts over the past several decades, from 1996 through 2010, are considered in the following section.

1.2.5 Future Predictions

As indicated in the population discussion, land conversion to developed or other human-influenced uses is likely to continue and possibly increase. Pressure on natural habitats as they are converted to development or to agricultural use (as agricultural land in turn is being developed) is significant, particularly in the lower portions of the Basin, where most of the population resides. Pressure on the natural systems, particularly forest and tidal wetlands, is a concern. The large tracts of forest in the upper Delaware River watersheds support the provision of clean drinking water to a significant portion of the U.S. population (e.g. New York City).

An adequate and clean flow of water is vital to the health of all downstream users along the main stem of the Delaware River. Pressures due to forest fragmentation stemming from high levels of commercial and residential development are likely to accelerate in the future. Pressures from hydraulic fracturing and its ancillary effects (roads, pipelines, supporting development) may also accelerate concern should natural gas production become more viable in the future. Wetland loss due to filling, development, and inundation is a significant concern in the tidal portions of the Basin and Estuary. Climate change and the concomitant increase in tidal and storm energy along with sea level rise is likely to exert increasing pressure in those areas.

Conservation efforts in urbanized areas, such as green infrastructure implementation, water conservation measures, and regional planning to help guide how and where growth occurs can offset some of the expected harmful pressures associated with that growth. Proper guidelines for activities such as hydraulic fracturing, along with well-informed coastal protection measures will go a long way toward protecting against the worst potential effects of land use and land cover changes.

1.2.6 Actions and Needs

The continued provision of high-quality, synoptic, normalized land cover data at repeated, fixed intervals will be needed to continue to monitor land cover and determine the status of the overall health of the Basin. Classified imagery provided by the NOAA CSC through their C-CAP program has proven invaluable in this effort. It is critical that national programs such as this and others be sustained and supported to allow ongoing monitoring and assessment of the status and trends in the watersheds of the Delaware River Basin.

Other regional or national efforts, such as the NLCD program or various state-sponsored land use/land cover efforts have proven less central in this and previous State of the Basin reports, but could be used in the future for verification or perhaps to augment the research.

1.2.7 Summary

The Delaware River Basin comprises 10 major watersheds across four regions: Upper, Central, Lower, and Bayshore. Overall, based on 2010 data, forests make up 48% of the land area, agriculture 24%, development 16%, and wetlands 9%. Land cover varies significantly across the Basin, with the most forest occurring in the northern-most watershed (East-West Branch), and development increasing toward the south. The Central Region can be considered a transition from the highly forested watersheds of the north of the Basin and the more urbanized southern portion, where in addition, most of the agriculture occurs. The highest proportion and amount of developed land occurs in the Upper Estuary watershed, which contains the City of Philadelphia. The watersheds of the Delaware Bayshore region are more agricultural and less developed than most others in the Basin, and contain a significant amount of tidal wetlands.

Land uses in the Lower Region (northern part of the Estuary) are nearly equally divided into forested, agriculture, and forest, a composition that implies a tension among these generally competing cover types. Most development (78% of the Basin total) is concentrated in the Estuary (particularly the upper portion) as is most (71%) of the Basin's wetlands (due to the extensive tidal wetlands along the Delaware Bay.

Suggested Citation for this Chapter

Homsey, A., L. Haaf, K. Somers. 2017. "Chapter 1.2 - Current Land Cover" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 31-40.

1.3 Land Cover Change

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1.3.1 Introduction

This analysis considers the net change in land cover based on the NOAA-CSC data for 1996, 2001, 2006, and 2010. It includes changes across the Delaware River Basin, by the six land cover types defined in Chapter 1.2: developed, agriculture, forest, wetlands, water and other (e.g. barren, transitional).

1.3.2 Description of Indicator

It is in the nature of landscapes to change over time. These changes may be driven by natural processes such as vegetative succession, erosion, wildlife migration, or natural climatic shifts. Such changes tend to be quite gradual, while changes occurring through human agency are often quite rapid and pronounced, including land development, building of infrastructure, extensive use of the land (e.g. agriculture, natural resource extraction, silviculture, etc.), and human migration. Other processes that are indirectly driven by human influence, such as climate change, sea level rise, climate disruptions, and invasive species dispersal, can also have significant impacts on the landscape.

In general, changes in aspects of land cover have resonating effects in terms of watershed health, provision of clean and abundant water, effectiveness of ecosystem services that landscapes can provide, and health and well-being of watershed residents, both human and non-human.

Land cover change does not inevitably change due to watershed degradation, but the location, extent, and nature of change bears directly on watershed health and the potential loss of the function of the natural landscape. Aggregate net changes in land cover may or may not be an indicator of landscape stressors, but can point planners and watershed managers to areas of potential concern. Further study or consideration of ameliorating measures may well be suggested by synoptic, landscape-scale assessments of land cover change. As a metric, land cover change is often an important factor in considering threats and opportunities within the Delaware River Basin.

1.3.3 Past Trends and Present Status

Land Cover Change in the Basin and Regions Changes in the landscape have generally been a "one-way street": once land is converted from a more natural to a more developed state (e.g. from forest to agriculture, or agriculture to residential development), it is unlikely to revert back to an earlier or more natural state. As former Secretary of Agriculture, Rupert Cutler, noted, "Asphalt is the land's last crop."

In the pre-Columbian era, the entire Basin was much more forested, even while Native Americans did exert considerable stress on the landscape across a wide area. By the early 20th century, forest cover was at its lowest ebb. Over the intervening century, economic trends, land use policies, and environmental protections have caused a "greening" of the Basin in inhabited areas. Over the same period, population in the nation and the Basin exploded. While there is some indication that increases are slowing, the number of people increasingly dispersed has led to development strains, particularly in the "transitional" watersheds of the Central Region. Broader economic and geopolitical forces have led to trends such as the increase in hydraulic fracturing for natural gas nationally, with the concomitant increase of related infrastructure (e.g., roads and pipelines) and ancillary development. While having seen a decrease in recent years due to a slump in global commodity and energy prices, pressure from hydraulic fracturing and associated uses could become a significant driver of land use change in the future.

As discussed in the previous section, the land cover information has been derived from NOAA CSC C-CAP data. Between the release of the 2006 and the 2010 era data, the land cover data was reclassified based on improved ground information. This difference results in a significant difference between data derived for the previous State of the Basin report (TREB 2012) and the current report. Based on the newly revised data, between 1996 and 2010:

- Approximately 187 square miles were developed across the Basin (an increase of 9.8%).
- 71 square miles of agricultural land was converted to another use or succumbed to natural succession and reverted to forest (a net loss of 2.2%).
- There was a net loss of over 105 square miles of forested land (a net loss of 1.7%).
- The Basin lost over 10 square miles of freshwater and tidal wetlands (a net loss of 0.8%).

See Table 1.3.1 for a summary of net changes (square miles) and the respective percent change within the regions of the Basin and the Basin overall. Figure 1.3.1 shows the overall changes in the Basin as well as in the Nontidal and Estuary portions.

Table 1.3.1 Summary of the net Land Cover changes (mi^2) with the Basin's region and the Basin overall from 1996-2010. Respective percent changes are in parenthesis.

Region	Land Cover Category					
	Developed	Agriculture	Forest	Wetland	Open Water	Other
Upper	5 (9%)	18 (4%)	-24 (-0.8%)	0 (0.1%)	1 (0.9%)	-1 (-3%)
Central	45 (13%)	-13 (-2%)	-31 (-2%)	0 (0%)	0 (0.2%)	-1 (9%)
Lower	116 (9%)	-64 (-4%)	-44 (-3%)	-5 (-1%)	1 (1%)	-3 (-13%)
Bayshore	20 (14%)	-12 (-2%)	-7 (-3%)	-5 (-1%)	3 (7%)	0 (0%)
Basin TOTAL	187 (10%)	-71 (-2%)	-105 (-2%)	-10 (-1%)	5 (2%)	-5 (-8%)

Total Change in Land Cover While satellite-based analyses are not suitable for small-scale studies, they provide valuable measures of relative and absolute changes across large areas. Figure 1.3.2 illustrates the net change in land cover type across the Basin by the ten watershed groups arranged north to south (reading left to right), between 1996 and 2010.

The overall increase in developed area is evident, particularly in the more "natural" watersheds of the Central Region: Upper Central and Lehigh Valley. Forested land is in decline across the watersheds, particularly in the northern-most, highly forested watershed (East-West), in the developing watersheds of the Central Region (Upper Central and Lehigh Valley), and several of the highly urbanized watersheds in the Philadelphia region (Schuylkill Valley and Upper Estuary).

The Table 1.3.2 summarizes the land cover changes (in square miles) in the Basin between 1996 and 2010 (percent changes are given in parenthesis).

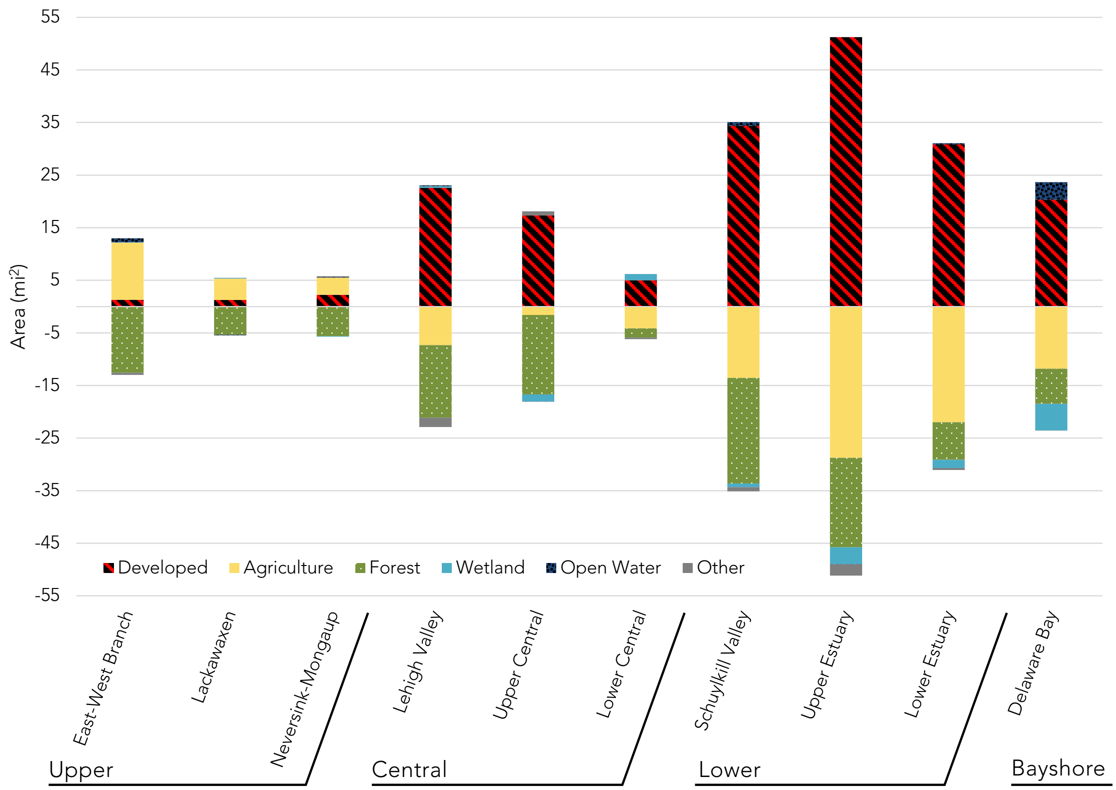

Figure 1.3.1 Change in Land Cover within watersheds, grouped by Region from 1996-2010. Regions are arranged north to south, from left to right.

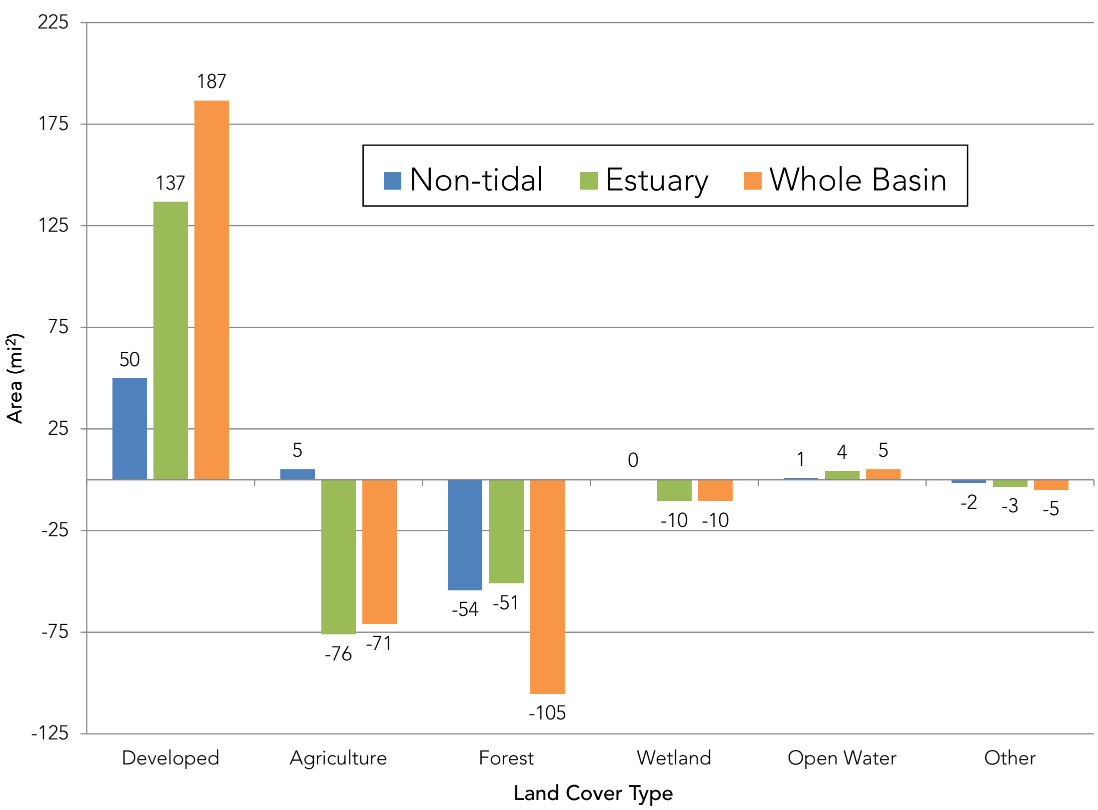

Figure 1.3.2 Change in Land Cover Type by each Basin division (Nontidal and Estuary), as well as the Basin as a whole, from 1996-2010. Numbers indicate exact areas in mi².

Rate of Land Cover Change The rate of change of land cover across the time period from 1996 to 2010 also varied (Fig 1.3.3). Developed land saw the largest increase, by percent in the years between 2001 and 2006. That period also saw the largest percentage loss of agricultural land and wetland.

The land cover changes occurring in the period between 1996 and 2010 translate to a daily loss of forest land of 12.3 acres (5 hectares) across the Basin. In addition, this translates to an additional 21.8 acres (8.8 hectares) of developed land each day, and a daily loss of 8.3 acres (3.4 hectares) of agricultural land and 1.2 acres (0.5 hectares) of wetlands.

Rate of Forest Change Forest loss is a significant component of overall land cover changes in the Delaware River Basin. Over the period from 1996 to 2010, the total percentage of forest loss was 2%. From 1996 to 2010, the rate of loss has accelerated across each approximate five-year period during that time frame. This is significant since the degree of forest cover in a watershed influences on the overall health: the higher the percentage of forested cover, the better the condition of the watershed and all waters downstream. Conversely, a larger proportion of development and hardened, impervious surfaces, the more degraded the water quality and overall health of a watershed (see Chapter 1.4). Figure 1.3.4 illustrates the acceleration of forest cover loss. These data indicate that there has been an increasing rate of loss in forest cover in the

Table 1.3.2 Summary of the net Land Cover changes (mi^2) with the Basin's watersheds, the Basin's divisions (Nontidal and Estuary), and the Basin overall, from 1996-2010. Percent changes are in parenthesis.

Region	Watershed	Developed	Agriculture	Forest	Wetland	Open Water	Other
Upper	East-West Branch	1.3 (6%)	11 (4%)	-13 (-1%)	0.1 (0.2%)	0.8 (3%)	-0.4 (-7%)
	Lackawaxen	1.3 (10%)	4 (4%)	-5 (-1%)	0.1 (0.2%)	-0.2 (-0.6%)	0.04 (8%)
	Neversink-Mongaup	2.3 (10%)	3 (11%)	-6 (-1%)	-0.1 (-0.2%)	0.10 (0.4%)	0.2 (10%)
Central	Lehigh Valley	23 (12%)	-7 (-3%)	-14 (-2%)	0.3 (0.4%)	0.10 (0.7%)	-1.8 (-16%)
	Upper Central	17 (15%)	-2 (-3%)	-15 (-2%)	-1.3 (-1%)	-0.01 (-0%)	0.8 (28%)
	Lower Central	5 (11%)	-4 (-2%)	-2 (-1%)	1.2 (6%)	-0.03 (-0.3%)	-0.3 (-21%)
Lower	Schuylkill Valley	34 (9%)	-14 (-2%)	-20 (-3%)	-0.7 (-2%)	0.80 (6%)	-0.8 (7%)
	Upper Estuary	51 (7%)	-29 (-8%)	-17 (-5%)	-3.2 (-1%)	-0.04 (-0.1%)	-2 (-18%)
	Lower Estuary	31 (31%)	-22 (-5%)	-7 (-3%)	-1.6 (-1%)	0.20 (7%)	-0.4 (-11%)
Bayshore	Delaware Bay	20 (14%)	-12 (-2%)	-7 (-3%)	-5 (-1%)	3 (0.6%)	-0.01 (-0.1%)
Basin TOTAL		187 (10%)	-71 (-2%)	-105 (-2%)	-10 (-1%)	5 (2%)	-5 (-8%)
NONTIDAL TOTAL		50 (9%)	5 (0.4%)	-54 (-1%)	0.2 (0.1%)	0.8 (0.6%)	-2 (-6%)
ESTUARY TOTAL		137 (10%)	-76 (-4%)	-51 (-3%)	-10 (-1%)	4 (3%)	-3 (-10%)

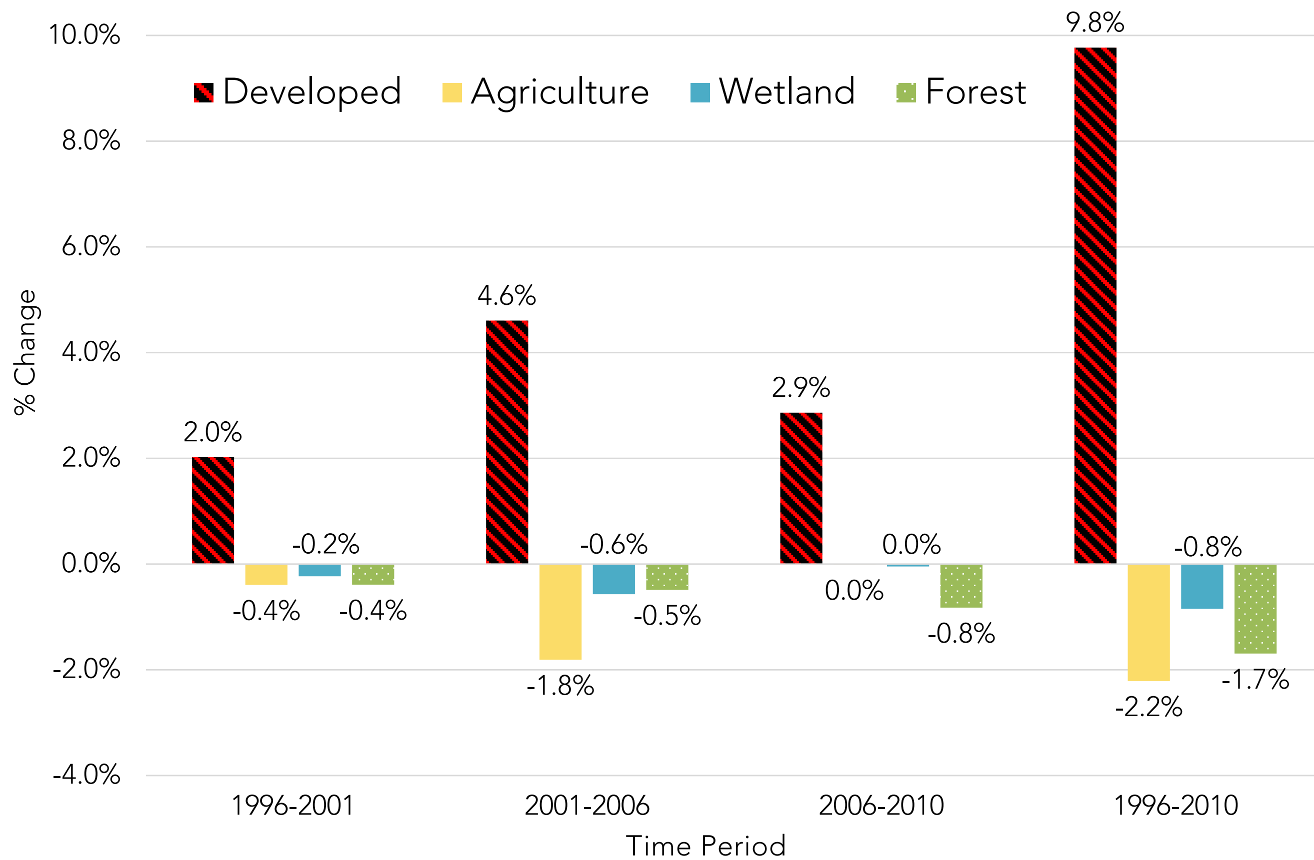

Figure 1.3.3 Rate of change for major land cover types across the Basin.

period between 2006 and 2010, -0.8% overall as compared to -0.5% and -0.4% decreases from 2001 to 2006 and from 1996 to 2001, respectively. While all forest types decreased in all periods, the deciduous loss was most marked in the period from 1996 to 2001, while all three types (deciduous, evergreen, and mixed) saw a significant acceleration of loss in the final period (2006-2010).

1.3.4 Future Predictions

Net land cover change in the landscape is part of the suite of indicators tracking how humans use the land and point to issues of concern that need more attention. Land cover change encapsulates other trends and activities, including demographic, economic, environmental, and regulatory. For example, economic recession has a bearing on where people settle, and where and to what degree development occurs. Large-scale climatic changes can have significant impacts on use of the land, including increased riverine flooding following rain events, landward migration of tidal wetlands as sea levels rise, or shoreline migration due to increased storm surge and tidal energy. Regulatory constraints on pollution, development, or land use have a direct impact on trends, and their cumulative effects can be great. Conversely, a lack of watershed planning can have detrimental effects on overall watershed health and vitality (ecological, economic, and demographic).

It is difficult to precisely predict where the land cover changes will occur, but it is clear where landscape changes are leading, as broad trends toward increased population and economic activity are nearly certain. With those factors, increased development pressure will follow. Efforts such as effective watershed-wide planning, open-space protection, agricultural protection, pollution control strategies, and smart growth policies can help assure that inevitable change will not be detrimental to the watershed or its human and other inhabitants. Forested lands and wetlands in particular bear special consideration due to their invaluable contributions to water quality and supply, habitat, and human well-being.

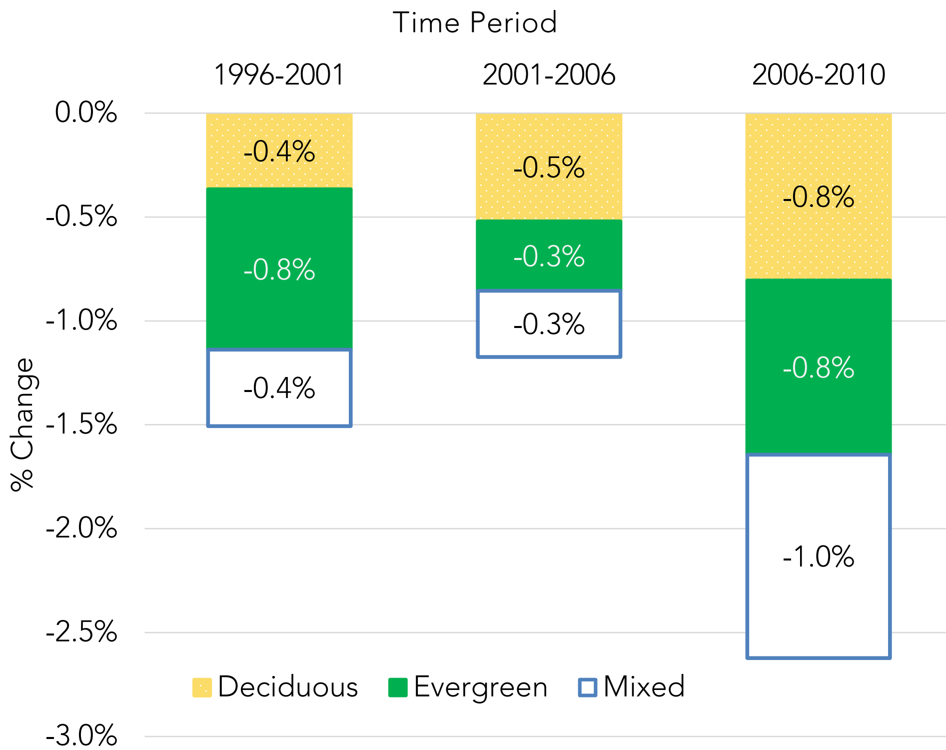

Figure 1.3.4 Rates of Forest type change across the Basin.

1.3.5 Actions and Needs

- Coordinated geospatial and other data collection, storage, and dissemination is key to being able to track and predict land cover changes.
- Focus on highly critical land cover types, such as wetlands and forest. Tracking of these land cover types should be emphasized and improved.
- Identification and inventory of forested areas critical to water resources and habitat.
- Identification and prioritization of the threats and opportunities for watershed protection across the Basin, recognizing that these will vary widely across the region.
- Prioritization of other areas for protection. This effort is in conjunction with broad watershed planning efforts.
- Coordination of prioritization and mapping efforts among local, state, regional, and federal regulatory agencies, local watershed groups and other non-profits, and the academic community.
- Coordinated efforts at restoration (for example, as is occurring with the William Penn Foundation whole Basin approach to watershed and water quality protection), aggregating and prioritizing funding, and potential remediation or preservation opportunities.
- Support for robust and comprehensive monitoring of progress and trends to inform decision makers and allow assessment of the success (or lack thereof) of programs.

1.3.6 Summary

Developed land increased in every watershed of the Basin in the 14 years between 1996 and 2010; a total of nearly 187 mi^2 (484 km^2) of land was developed. In aggregate the Basin lost over 76 mi^2 (197 km^2) of agriculture, nearly 51 mi^2 (132 km^2) of forest, and more than 10 mi^2 (26 km^2) of wetlands. The Estuary portion of the watershed experienced the highest increase in development (73%), almost half (48%) of the forest loss, and nearly all the agricultural (93%) and wetland (98%) losses experienced across the Basin.

The watersheds of the Lower Region experienced the greatest increases in developed land as well as the most loss of agricultural land and forest. As a percentage increase, however, both the Central and Bayshore Regions saw more intensive development pressure. Forests also saw large decreases in the Upper and Central Regions, but less in the Bayshore Region (where there is less forested land to begin with). The Lower and Bayshore Regions experienced the largest loss of wetlands in absolute and percent change terms.

While land conversion from forest and agriculture to developed land is expected to continue, a lower rate of population increase and economic trends may lead to decreased development pressure (e.g. decrease in natural gas extraction by hydraulic fracturing). This is particularly the case in previous expansion of the Central Region. If energy prices spike in the future, it is expected that increased pressure on extractive industries in the fragile forested upper Regions will occur.

Suggested Citation for this Chapter

Homsey, A., L. Haaf, K. Somers. 2017. "Chapter 1.3 - Land Cover Change" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 41-47.

1.4 Impervious Cover

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1.4.1 Description of Indicator

Impervious cover is defined as ground features that prevent water from infiltrating into the ground and as a result cause water to run off to adjacent areas. Imperviousness as a watershed metric is the measure of the degree to which an area of the ground is covered by such features, which include roads, parking lots, rooftops, and any other hard or impermeable surfaces. Imperviousness disrupts the normal hydrologic cycle, in which a portion of water from precipitation percolates into the ground. Impervious cover causes water that might otherwise have recharged the ground water table to run off, often increasing the amount of water and suspended pollutants entering streams and other waterbodies. The measure of imperviousness is an indication of the overall health of a watershed. A high percentage of impervious cover leads to more polluted waters, and streams which flood more during storms and flow less during dry times relative to more natural areas, such as forests or meadows.

A survey of 225 research projects assessing the degree of correlation of impervious cover stream and aquatic life condition compiled by the Center for Watershed Protection links the presence of impervious cover to several negative impacts, including:

- Reduced macroinvertebrate and fish diversity
- Decline in biological function
- Increase in stream temperature
- Decline in channel stability and fish habitat
- Compromised wetlands water quality and water level fluctuation

The Center for Watershed Protection notes that…

"When evaluating the direct impact of urbanization on streams, researchers have emphasized hydrologic, physical and biological indicators to define urban stream quality. In recent years, impervious cover (IC) has emerged as a key paradigm to explain and sometimes predict how severely these stream quality indicators change in response to different levels of watershed development . . .

Quite simply, the influence of IC in the one to 10% range is relatively weak compared to other potential watershed factors, such as percent forest cover, riparian continuity, historical land use, soils, agriculture, acid mine drainage or a host of other stressors. Consequently, watershed managers should never rely on IC alone to classify and manage streams in watersheds with less than 10% IC. Rather, they should evaluate a range of supplemental watershed variables to measure or predict actual stream quality within these lightly developed watersheds."[1]

1. Center for Watershed Protection 2003. Impacts of Impervious Cover on Aquatic Systems. Watershed Protection Research Monograph No.1. Center for Watershed Protection, Ellicott City, Maryland 2003. www.cwp.org.

The deleterious effects of imperviousness generally become pronounced when the percentage of impervious cover is between 3% and 10% of land area; land areas with imperviousness above 15% is generally considered highly negatively impacted.

Figure 1.4.1 presents the Center for Watershed Protection's model of impervious cover impacts on streams. Note that there are not "hard breaks" in the curves, recognizing that the quality of imperviousness varies greatly (for instance, the effects of imperviousness vary with the degree to which it is connected directly to streams, or whether infiltration techniques are present, etc.). In a watershed with above about 10% imperviousness the streams are considered "Impacted," while over 25% imperviousness is considered "Nonsupporting" for streams in terms of habitat.

Data source and processing methodology Measures of impervious cover can be derived in several ways. Using remotely-sensed (satellite) data is a common method for compiling imperviousness across a large area. Often data, such as the USGS generated layers in conjunction with the National Land Cover Classification project, present impervious data as a percentage of non-porous land cover in a given area (e.g., one pixel in a geographic image). The data are derived using remote sensing and image processing techniques; the value, or color of the pixel represents a proportion of imperviousness at that location. These types of data are useful for large areas, when total acreage values are not the prime concern. They have the advantage of being well coordinated between dates, and typically are reproduced at a relatively short time interval (several years), but often provide only rough estimates of actual imperviousness on the ground. For example, the NL-CD-derived data masks out areas that are considered "undeveloped," even where development exists, but at a relatively low density.

Another common method to calculate imperviousness is the delineation of actual hard surfaces based on aerial photography. Depending on the methodology and scale of photography, these can be highly detailed and accurate. The drawback is that finding comparable data across a wide area (particularly across state lines,

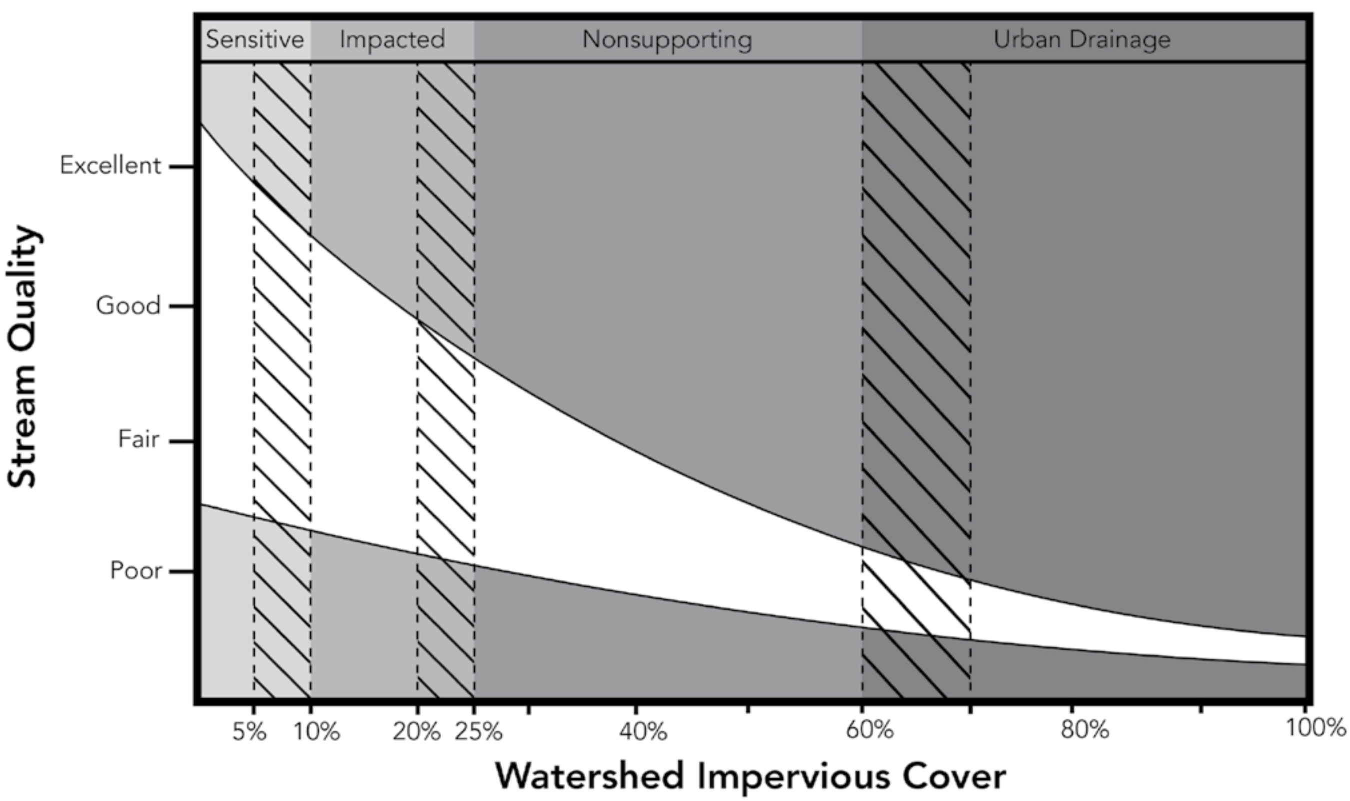

Figure 1.4.1 Center for Watershed Protection's model of impervious cover impacts on streams.

as these data are often produced under state-sponsored programs), and at a reasonable repeat interval, is often difficult if not impossible. To track changes and compare across a region, the data must be compiled using similar techniques (same scale, date of photography, etc.). Unfortunately, this is almost never the case.

For the previous TREB (2012) and for the present analysis, another technique was chosen that uses land cover as a proxy based on associated representative imperviousness values (as a percent). This technique has the advantage of being simple to understand and replicate, and transparent in terms of how the data were derived. The NOAA CSC C-CAP land cover data series is a fairly detailed (in terms of spatial resolution and categories) synoptic (i.e., covering the region seamlessly) data source produced at a five-year interval. This data source provides a consistent and comparable snapshot across the entire Basin. By applying the same representative value for each land cover category, relative changes across time can be assessed. While the exact degree of imperviousness cannot be measured directly (for instance, the proxy imperviousness value for a land cover type clearly does not apply to all instances of that type on the ground), the degree of imperviousness broadly, and the relative degree of imperviousness across the Basin and through time, can be determined. Table 1.4.1 summarizes the land cover types found in the C-CAP land cover data (from 1996, 2001, 2006, and 2010), along with their representative impervious cover (IC) percentage factors.

Table 1.4.1 Impervious Cover Factor by C-CAP Land Cover Type.*

C-CAP code	C-CAP class	I.C. factor
2	High Intensity Developed	0.85
3	Medium Intensity Developed	0.6
4	Low Intensity Developed	0.3
5	Open Spaces Developed	0.08
6	Cultivated Land	0.02
7	Pasture/Hay	0.02
8	Grassland	0.02
9	Deciduous Forest	0.02
10	Evergreen Forest	0.02
11	Mixed Forest	0.02
12	Scrub/Shrub	0.02
13	Palustrine Forested Wetland	0
14	Palustrine Scrub/Shrub Wetland	0
15	Palustrine Emergent Wetland	0
16	Estuarine Forested Wetland	0
17	Estuarine Scrub/Shrub Wetland	0
18	Estuarine Emergent Wetland	0
19	Unconsolidated Shore	0.1
20	Bare Land	0.1
21	Water	0

*See TREB 2012 for more info.

1.4.2 Present Status

Impervious cover in the Delaware River Basin varies dramatically across its 21 watersheds. In general, where there is more development, imperviousness also increases. Higher levels of imperviousness lead to disruptions of the hydrologic cycle, including increased stream flashiness leading to urban flooding problems, greater transport of pollution, increased stormwater runoff, reduced water tables, and reduced stream base flows. This metric, therefore bears directly on ill effects due to increased flooding, altered stream geomorphology, degraded water quality, diminished or depleted aquatic habitat, and decreased water supply, for both surface and groundwater. The map in Figure 1.4.2 shows the watersheds of the Delaware River Basin characterized by overall level of imperviousness (as a percent).

Figure 1.4.3 presents the current (2010) imperviousness, by watershed in the Delaware River Basin, as a percent of land cover. The red line in the graph indicates the level of imperviousness above which streams are considered "Impacted" according to the Center for Watershed Protection's Impervious Cover Model (ICM).

The only watershed that is "Impacted" (at 185 imperviousness) for stream habitat is the Upper Estuary in Pennsylvania, which includes the densely developed area around Philadelphia. The Philadelphia greater regional area also has impervious values approaching the "Impacted" level, including the Lehigh Valley, Schuylkill Valley, and the Lower Estuary. Note that while the scores only indicate one sub-basin as being "Impacted," at smaller scales (watershed and sub-watershed), there are areas of much higher impact based on imperviousness.

1.4.3 Past Trends

By applying the same representative impervious values to land cover data from different periods, it is possible to track the trend in imperviousness across the watersheds of the Delaware River Basin. As has been discussed in Chapter 1.2 – Current Land Cover, NOAA CSC's C-CAP land cover data provides a consistent and detailed set of data layers at a five year interval, dating back to 1996. The trends closely match the trends for development in the watersheds. In general, the more highly urbanized areas of the Lower Region are also experiencing the highest rates of imperviousness increases. Table 1.4.2 shows the level of imperviousness in the period 1996 to 2010, for each watershed of the Delaware River Basin. Table 1.4.3 shows the values by region within the Basin. The shaded portions of the tables indicate watersheds of the Delaware Estuary.

Figure 1.4.4 presents the trend in imperviousness for the four time periods (1996, 2001, 2006, and 2010). While imperviousness is increasing in all watersheds, the rate of increase as well as the overall levels are highest in the Upper Estuary, followed by the other urbanizing watersheds of the Lehigh Valley, Schuylkill Valley, and the Lower Estuary.

Figure 1.4.5 shows the rate of change in imperviousness for each watershed over the period 1996 to 2010. While the urbanized watersheds of the Lower Region and Bayshore saw the highest percentage increase in imperviousness in the middle period between 2001 and 2006, the Lehigh Valley in the Central Region saw the percentage of imperviousness spike in the last period, between 2006 and 2010.

1.4.4 Future Predictions

While there is a clear increase in imperviousness in the watersheds of the Delaware River Basin, future directions will be dependent on the trajectory of land cover, demographic, and economic trends. The negative impacts of imperviousness are potentially lessened by proper watershed management promulgated through local and regional planning efforts. Stormwater regulations in particular can help channel funding into efforts at reducing runoff and increasing infiltration of rainwater. Both trends are likely to continue.

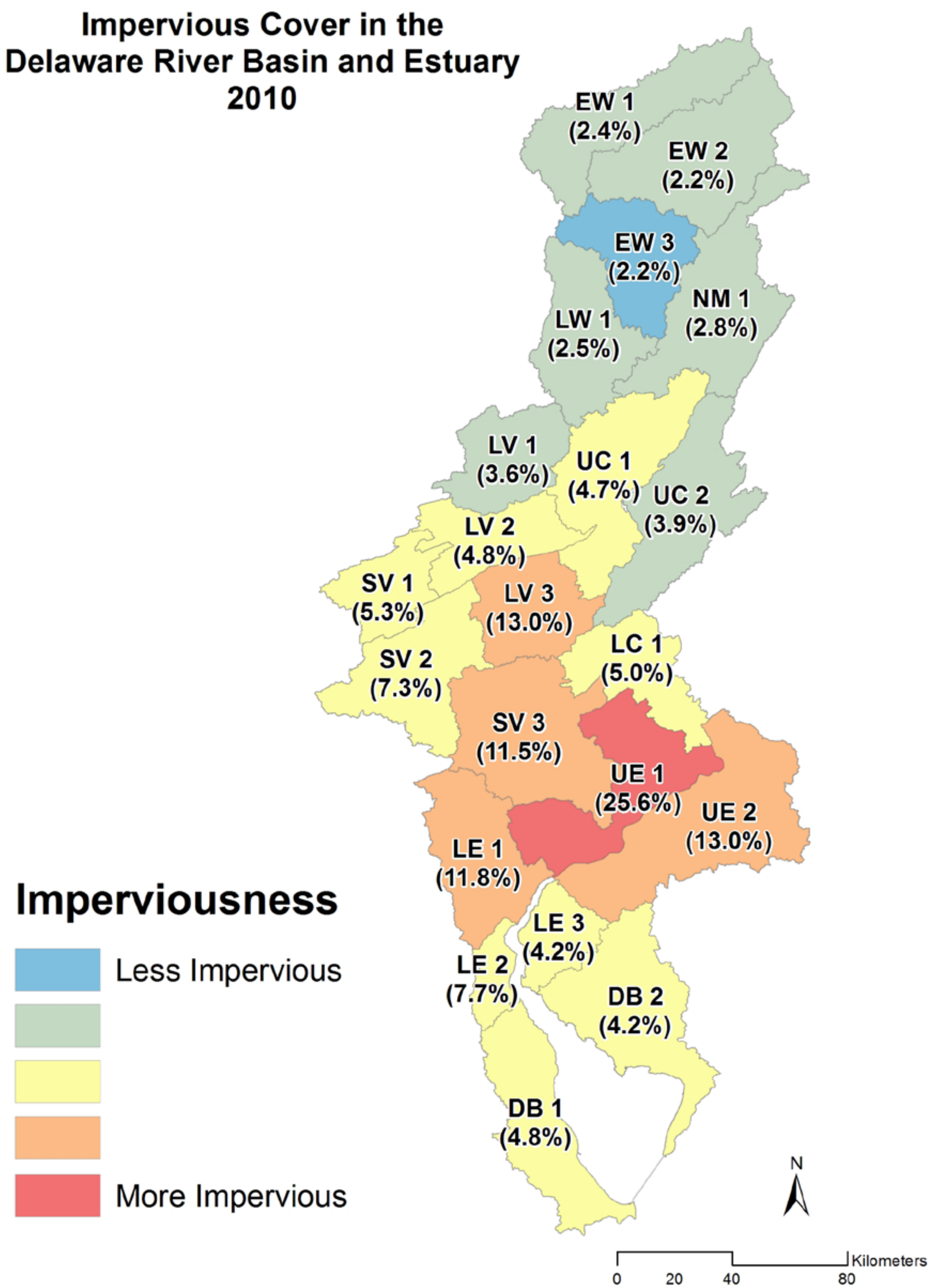

Figure 1.4.2 Watersheds of the Basin characterized by overall level of imperviousness (%). Reference Fig 0.7 for abbreviation legend.

As flooding becomes more common due to climatic changes, it is possible that flood control measures reducing the impact of impervious surfaces may become more widely implemented. Studies taken at smaller, catchment levels will be necessary to determine in more detail the extent and effects of imperviousness, and of efforts to ameliorate it.

1.4.5 Actions and Needs

To track watershed-scale trends in impervious cover, it is important that efforts such as the NOAA CSC C-CAP program remain viable. Even temporary suspension of data compilation can hamper efforts at planning to mitigate the effects of development, and specifically impervious cover. Detailed, high-resolution studies are also important, but are difficult to translate across the region. Efforts such as generation of Basin-wide land cover at a 1 meter resolution as well as development trend modeling through the Delaware River Basin Initiative (DRWI; led by The Academy of Natural Sciences of Drexel University, see http://www.ansp.org/research/environmental-research/projects/watershed-protection-program/), undertaken by the University of Vermont Spatial Analysis Laboratory in collaboration with Shippensburg University, will be invaluable in these efforts.

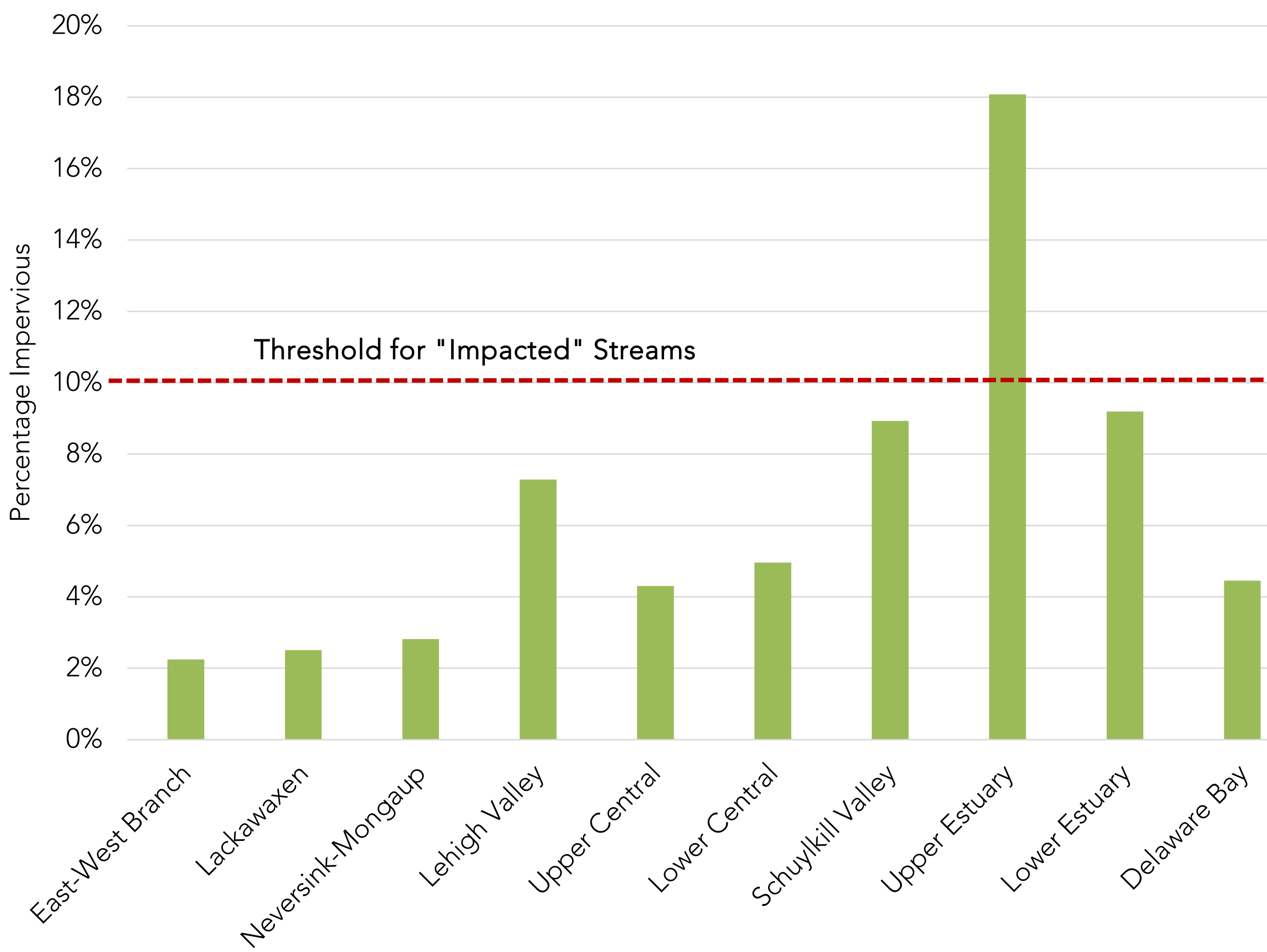

Figure 1.4.3 Current (2010) percent land cover imperviousness by watershed in the Delaware River Basin.

Table 1.4.2 Percent impervious cover by watershed in each Region of the Basin.

Region	Watershed	IC 1996	IC 2001	IC 2006	IC 2010
Upper Region	East-West Branch	2.2%	2.2%	2.2%	2.2%
	Lackawaxen	2.4%	2.4%	2.5%	2.5%
	Nevesink-Mongaup	2.7%	2.7%	2.8%	2.8%
Central Region	Lehigh Valley	6.6%	6.7%	6.9%	7.3%
	Upper Central	3.9%	4.0%	4.1%	4.3%
	Lower Central	4.6%	4.7%	4.9%	5.0%
Lower Region	Schuylkill Valley	8.2%	8.3%	8.7%	8.9%
	Upper Estuary	16.9%	17.2%	17.7%	18.1%
	Lower Estuary	8.2%	8.5%	8.9%	9.2%
Bayshore	Delaware Bay	4.1%	4.1%	4.4%	4.5%

Table 1.4.3 Percent impervious cover for each Region of the Basin.

Region	IC 1996	IC 2001	IC 2006	IC 2010
Upper Region	2.4%	2.4%	2.4%	2.4%
Central Region	5.1%	5.2%	5.3%	5.6%
Lower Region	11.4%	11.7%	12.1%	12.4%
Bayshore	4.1%	4.1%	4.4%	4.5%

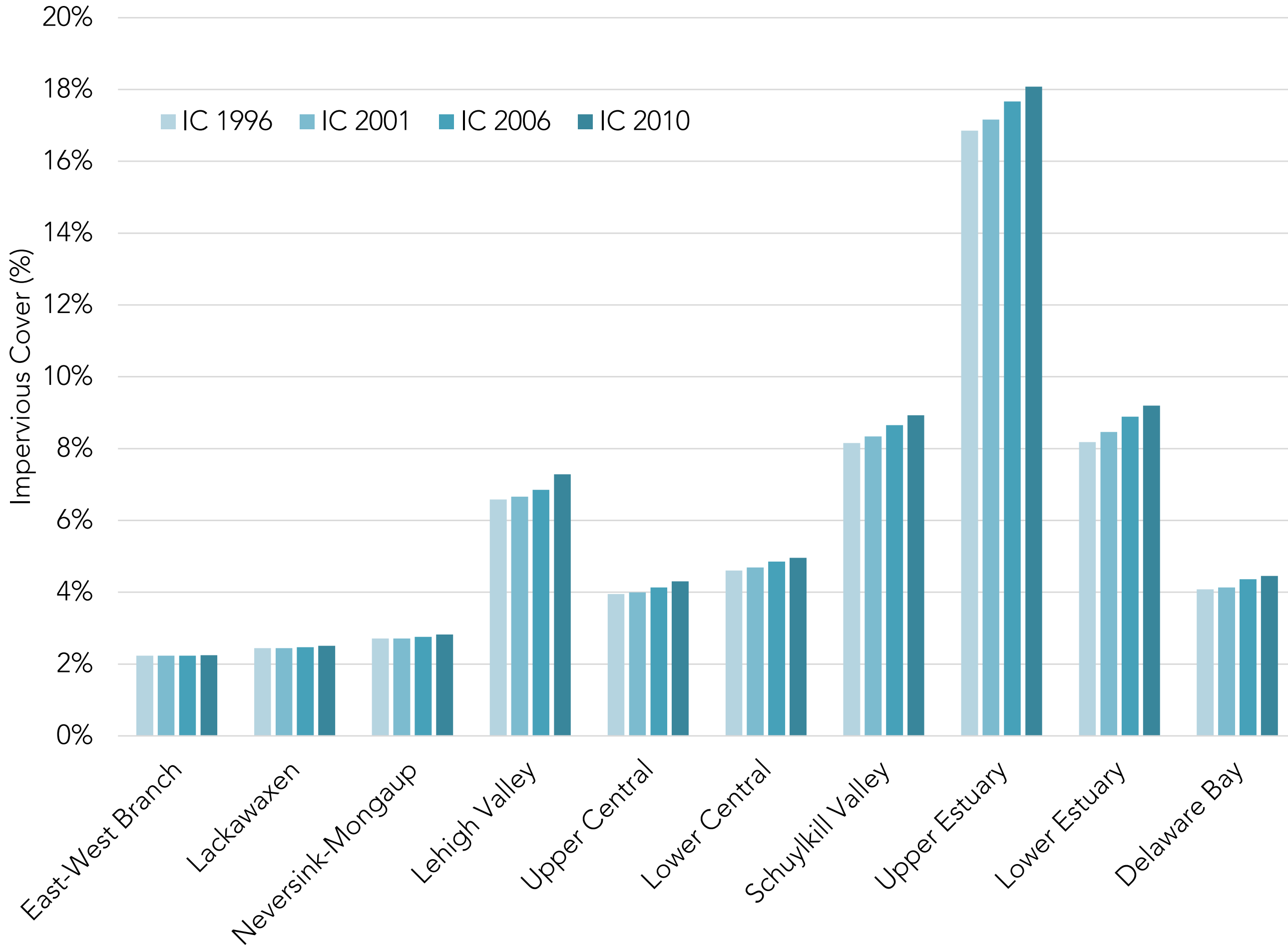

Figure 1.4.4 Percent impervious cover trends for the watersheds of the Basin for the four time periods analyzed: 1996, 2001, 2006, and 2010.

Increased coordination of efforts to control stormwater through the USEPA's National Pollutant Discharge Elimination System (NPDES) will be important to assure that resources are properly allocated. Watershed planning efforts should continue at the regional level. The DRWI and organizations such as the Delaware River Basin Commission and the Partnership for the Delaware Estuary should play a larger and more central role in coordinating these efforts.

1.4.6 Summary

Impervious cover has been identified as a key metric for tracking and predicting watershed health in terms of water volume, water quality, stream and riparian habitat, and drinking water supply. In many cases, regulations, such as Delaware's NPDES, specifically address impervious cover (DNREC, 2013).

The trend in increased imperviousness will threaten watersheds at all scales, but particularly on smaller, more urbanizing catchments. Treating water from runoff is expensive; it is more cost efficient to develop effective watershed plans, and to avoid creating as much hardened surfaces in the first place. The benefits to all aspects of watershed health and human well-being are well documented.

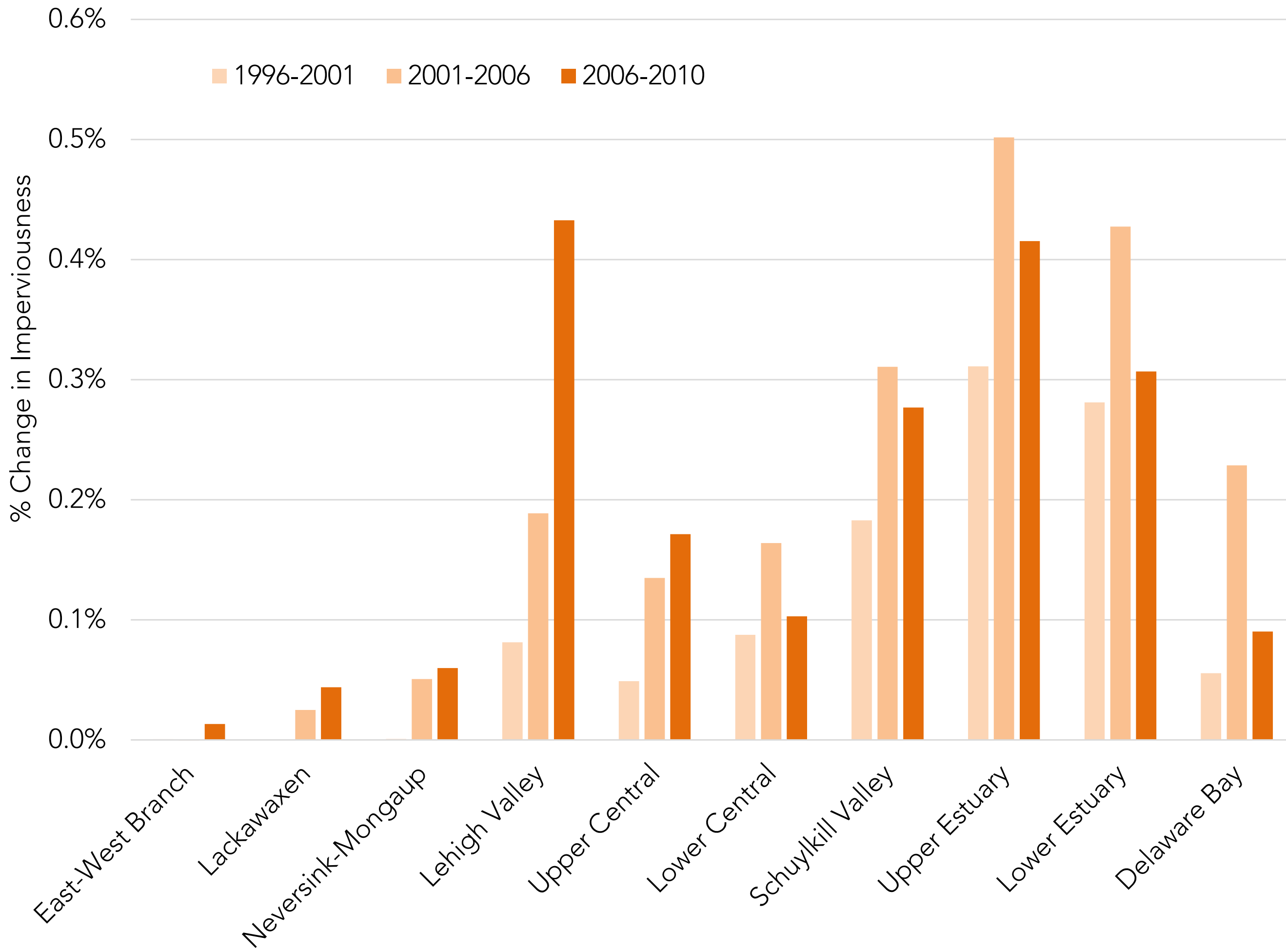

Figure 1.4.5 Percent change in imperviousness for the watersheds of the Basin.

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Center for Watershed Protection. 2003. Impacts of Impervious Cover on Aquatic Systems. Watershed Protection Research Monograph No.1. Center for Watershed Protection, Ellicott City, Maryland 2003. www.cwp.org.

Delaware Department of Natural Resources and Environmental Control (DNREC). 2013. Authorization to Discharge under the National Pollutant Discharge Elimination System and the Laws of the State of Delaware. NPDES Permit Number: DE0051071, State Permit Number: WPCC 3063A/96, effective date: May 7, 2013, expiration: May 6th, 2018.

Suggested Citation for this Chapter

Homsey, A., L. Haaf, K. Somers. 2017. "Chapter 1.4 - Impervious Cover" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 48-56.

1.5 Public Open Space

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1.5.1 Description of Indicator

Public open land is defined as Federal, state, local parks and conservation easements accessible to the public and where urban and suburban development cannot occur. Watersheds with high amounts of protected land usually have healthier streams and habitat.

The United States Geological Survey's (USGS) Gap Analysis Program (GAP) has tracked the location and extent of public open space through their Protected Areas Database of the United States (PAD-US). The data are derived from a wide variety of sources, in particular state-level databases. The program inventories varying types of open land with public access, including lands of federal, regional authority, state, local, and private ownership (individual or through non-governmental organizations) that provides the public access to open space, including fee-simple and eased lands. Data, particularly for these latter categories, are often difficult to obtain, but the PAD-US provides probably the most comprehensive and consistent snapshot of public open lands available. The present study looked at data from two years, 2010 and 2016. Table 1.5.1 presents the categories of land ownership defined in the PAD-US program.

Table 1.5.1 Categories of land ownership defined in the PAD-US program.

Domain Code	Domain Description
01	Federal
02	Native American
03	State
04	Special District
05	Local Government
06	Non-Governmental Organization
07	Private
08	Jointly Owned
09	Unknown Land Owner
10	Territorial

USGS Gap Analysis Program

The mission of the USGS Gap Analysis Program (GAP) is providing state, regional and national assessments of the conservation status of native vertebrate species and natural land cover types and facilitating the application of this information to land management activities. The PAD-US geodatabase is required to organize and assess the management status (i.e. apply GAP Status Codes) of elements of biodiversity protection. GAP seeks to increase the efficiency and accuracy of PAD-US updates by leveraging resources in protected areas data aggregation and maintenance as described in "A Map of the Future," published following the PAD-US Design Project (July, 2009) available at: http://gapanalysis.usgs.gov/padus/vision/ with updates coming soon. While PAD-US was originally developed to support the GAP Mission stated above, the dataset is robust and has been expanded to support the conservation, recreation and public health communities as well. Additional applications become apparent over time. See the GAP Website http://gapanalysis.usgs.gov/padus/resources/ or the companion site http://protectedlands.net/uses for more information.

1.5.2 Present Status

Within the Basin, protected public open space as of 2016 covers approximately 1,950 square miles, or 15% of the land area of the Basin. Most of this land, 1,256 square miles, is owned by the states, with the next largest category being land owned by counties or localities, 286 square miles. Federal lands comprise 139 square miles of the total, with private lands making up 175 square miles.

Table 1.5.2 presents the total land area, area of public open space, and percentage of open space within each watershed and sub-watershed of the Delaware River Basin. Shaded cells indicate watersheds of the Delaware Estuary, while non-shaded cells represent nontidal watersheds. Figure 1.5.1 shows the percentage of each sub-watershed, from north to south reading left to right. Figure 1.5.2 shows the locations of open space with public access in the Basin, by ownership type. Figure 1.5.3 presents the percentage of all open space in the Basin as a percentage of each sub-watershed.

Table 1.5.2 Total land area, total open space, and percent open space of watersheds in the Basin.

Region	Watershed	Total Area (mi²)	Open Space (mi²)	% Open Space
Upper	East-West 1	665.5	95.5	14%
	East-West 2	840.1	226.0	27%
	East- West 3	523.2	42.6	8%
	Lackawaxen	597.3	58.0	10%
	Neversink-Mongaup	815.5	165.5	20%
Central	Lehigh Valley 1	450.9	170.5	38%
	Lehigh Valley 2	430.0	41.8	10%
	Lehigh Valley 3	479.3	21.8	5%
	Upper Central 1	778.3	163.5	21%
	Upper Central 2	744.4	176.4	24%
	Lower Central	453.5	45.3	10%
Lower	Schuylkill Valley 1	341.7	42.5	12%
	Schuylkill Valley 2	655.5	56.1	9%
	Schuylkill Valley 3	893.2	50.5	6%
	Upper Estuary 1	701.0	31.3	4%
	Upper Estuary 2	1,041.7	112.7	11%
	Lower Estuary 1	602.8	38.8	6%
	Lower Estuary 2	262.3	21.4	8%
	Lower Estuary 3	154.8	33.0	21%
Bayshore	Delaware Bay 2	788.1	175.0	22%
	Delaware Bay 1	632.3	181.7	29%
Division	**Estuary**	**6,073.3**	**743.0**	**12%**
	Nontidal	6,778.0	1,207.0	18%
	Delaware River Basin	12,851.3	1,950.0	15%

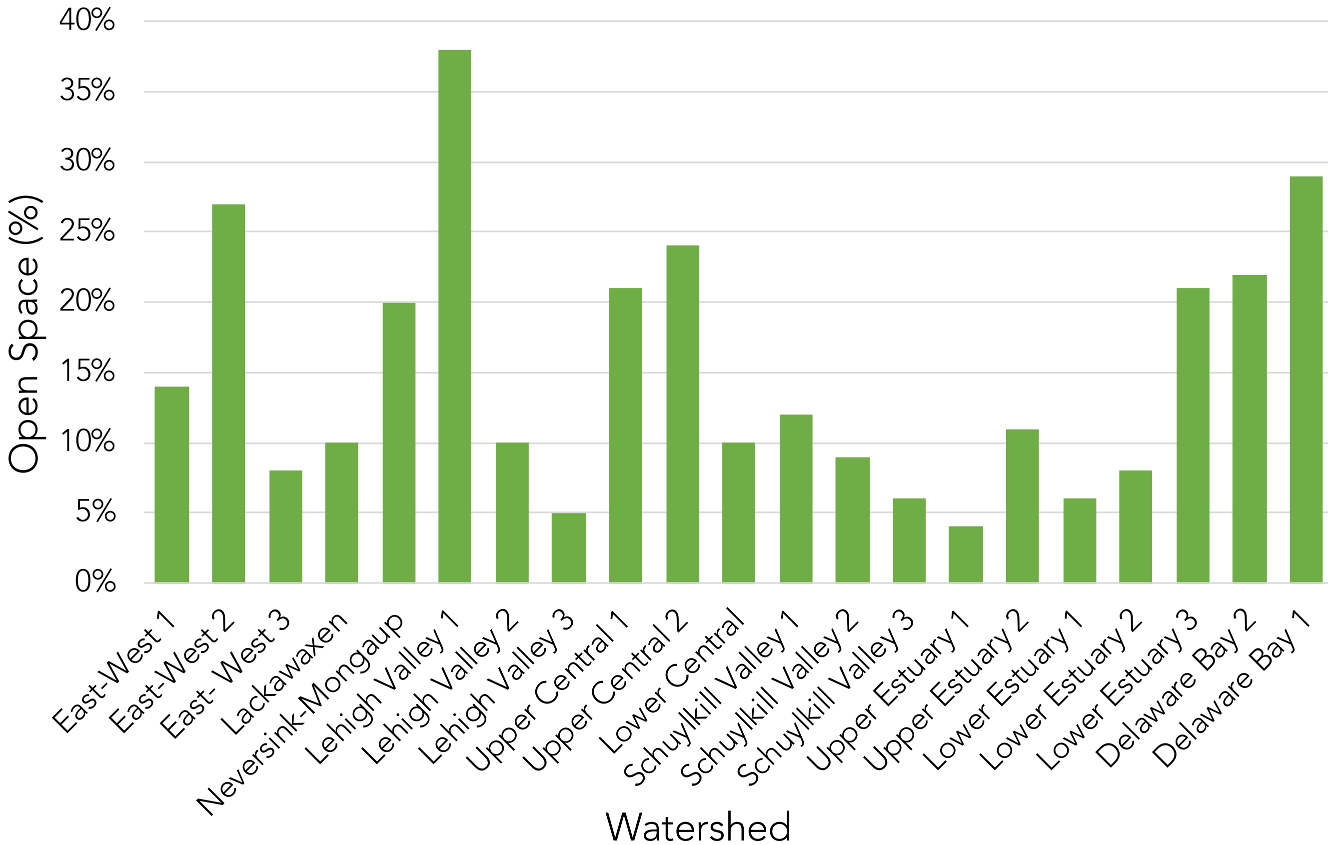

Figure 1.5.1 Percent open space of watersheds in the Basin.

1.5.3 Past Trends

Publicly accessible open space tends to be fairly stable over time, with relatively few large gains or losses. At the very local level, any changes will make a significant impact on the amount of public open space, which can have large effects on water quality, recreation, and overall human and non-human well-being. Through the USGS Protected Areas Database of the United States (PAD-US) program it was possible to compare two fairly recent snapshots of the location and extent of publicly accessible open space in the Delaware River Basin, in 2010 and 2016.

Figure 1.5.4 shows the change, by ownership type, of the amount of publicly accessible open space in the Basin in 2010 and 2016, according to the PAD-US database. Note that absolute changes are relatively small, with the only appreciable increase coming in the amount of county and local, and private land.

Figure 1.5.5 shows the percentage change over the period from 2010 to 2016 of all publicly accessible open space in the Delaware River Basin. As a percentage increase, the forested watersheds of the northern part of the Basin have experienced the most increase in open space in recent years, with significant increases also seen in the Upper Central, Lower Central, Lower Estuary, and Delaware Bay watersheds.

1.5.4 Future Predictions

While it is unlikely that large changes will occur in coming years, efforts, particularly in local and private preservation (through purchase or easement), are ongoing, and likely to produce significant improvements in total area of open space. This trend will provide benefits to water quality, habitat, and human and non-human use of the watershed.

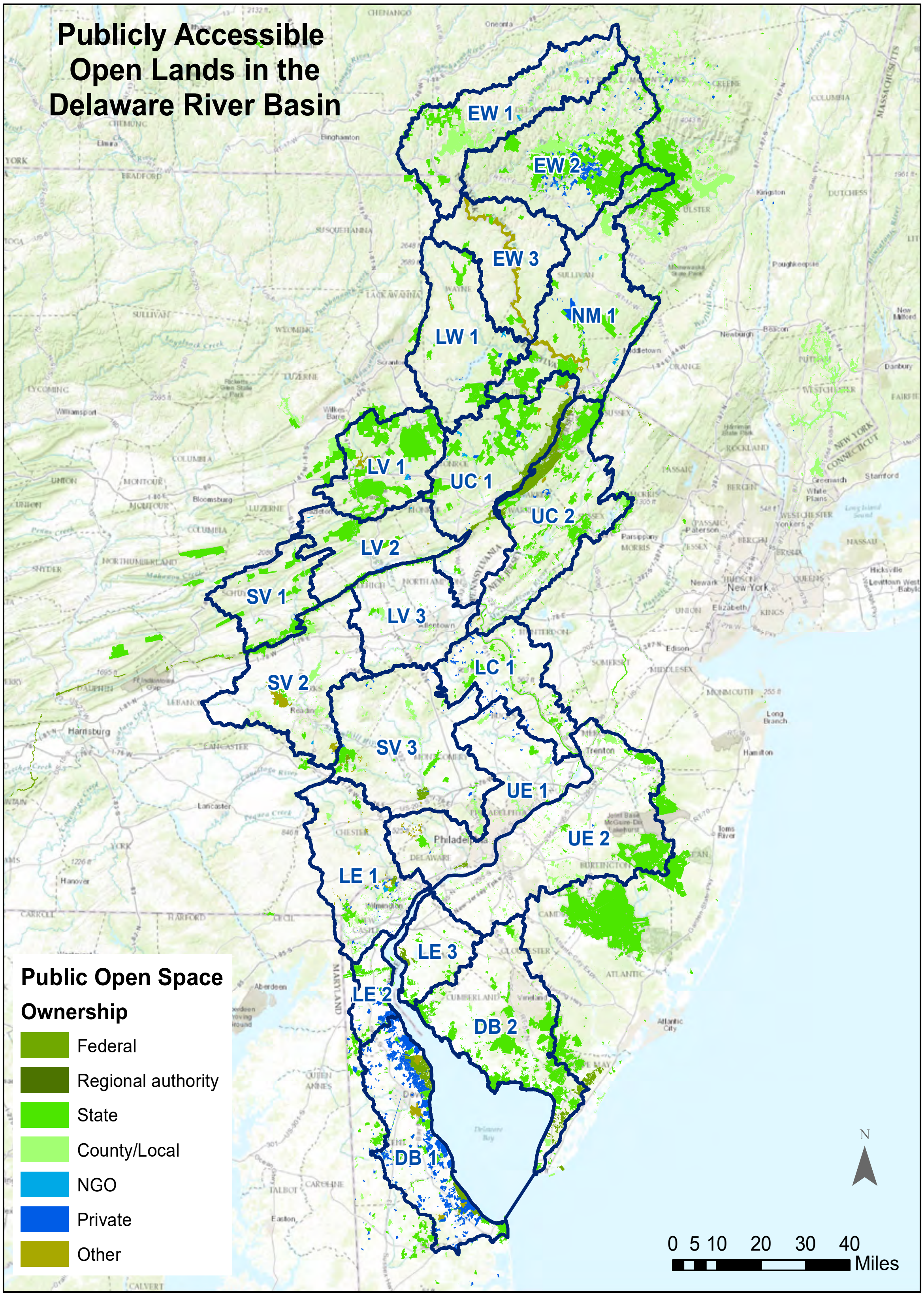

Figure 1.5.2 Spatial distribution of publicly accessible open space in the Basin for 2016 by ownership type. Reference Fig 0.7 for abbreviation legend.

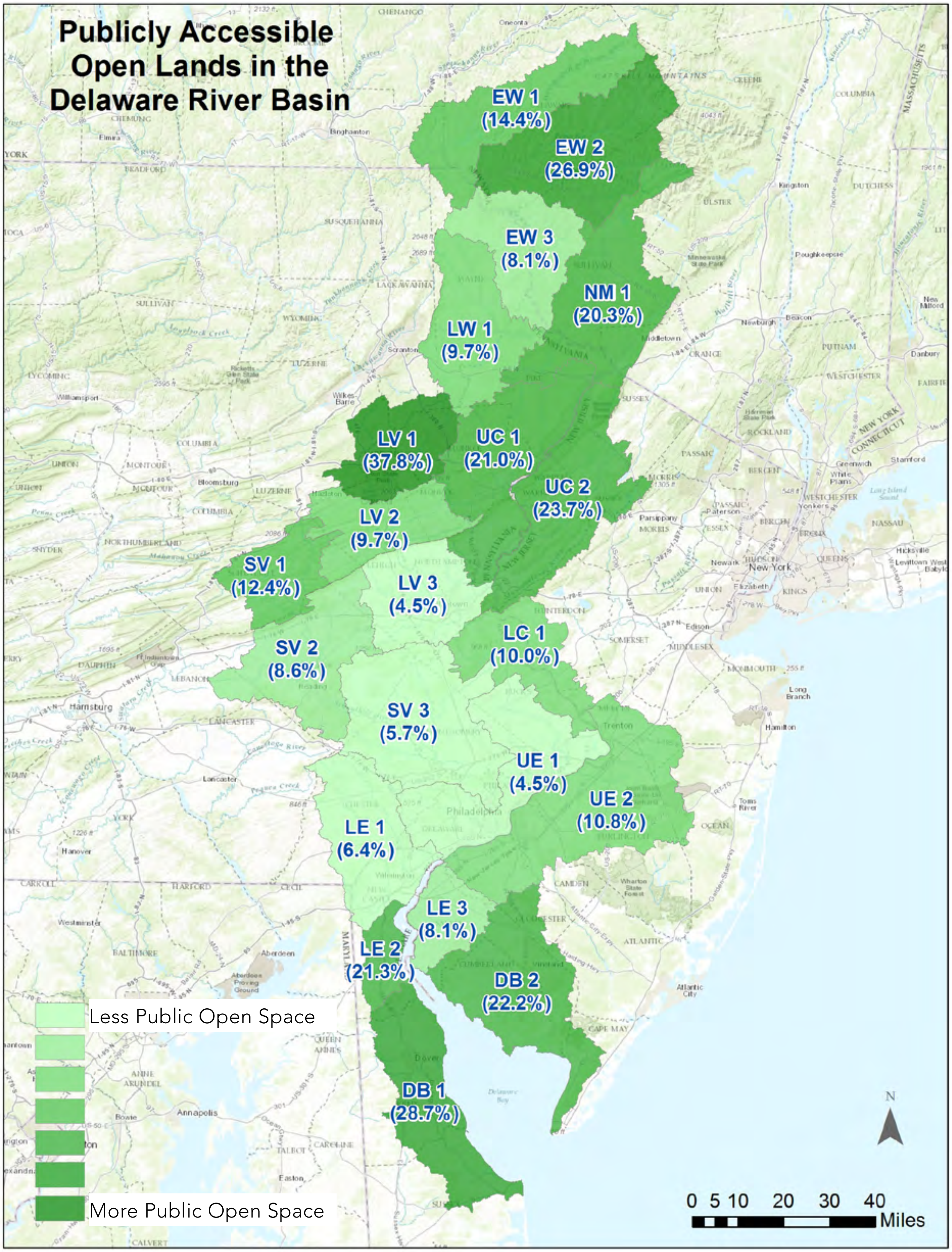

Figure 1.5.3 Percent of open space land cover within each watershed of the Basin. Reference Fig 0.7 for abbreviation legend.

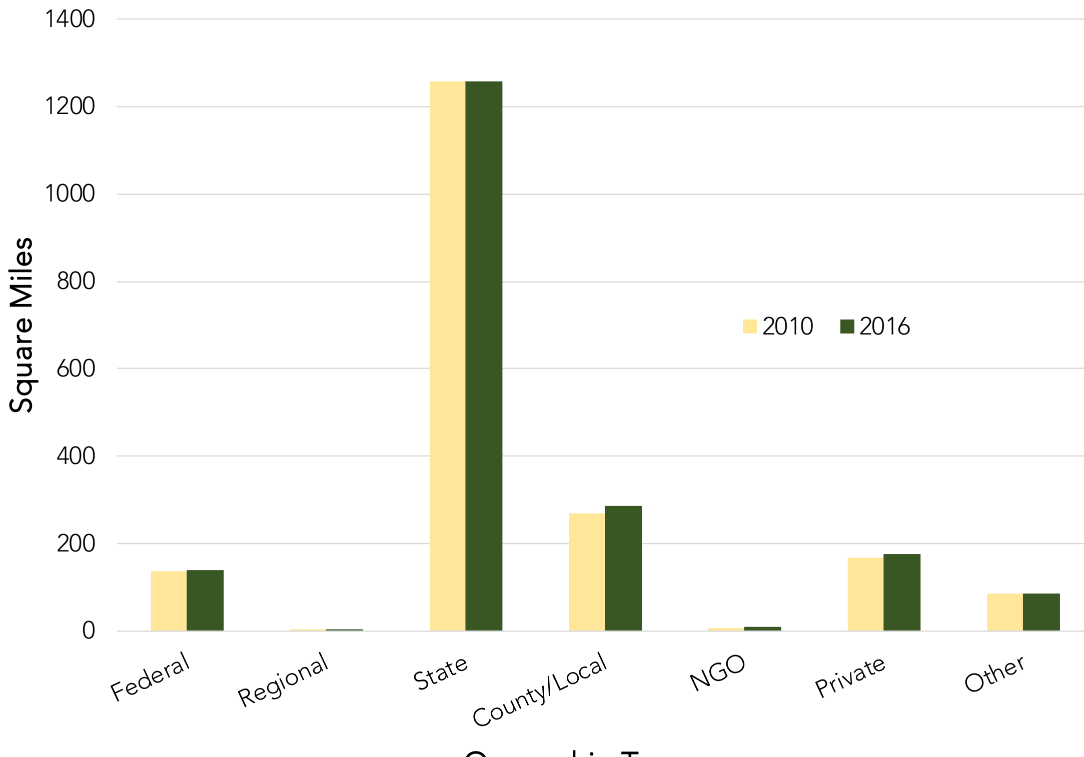

Figure 1.5.4 Public open land (mi²) in the Delaware River Basin for 2010 and 2016.

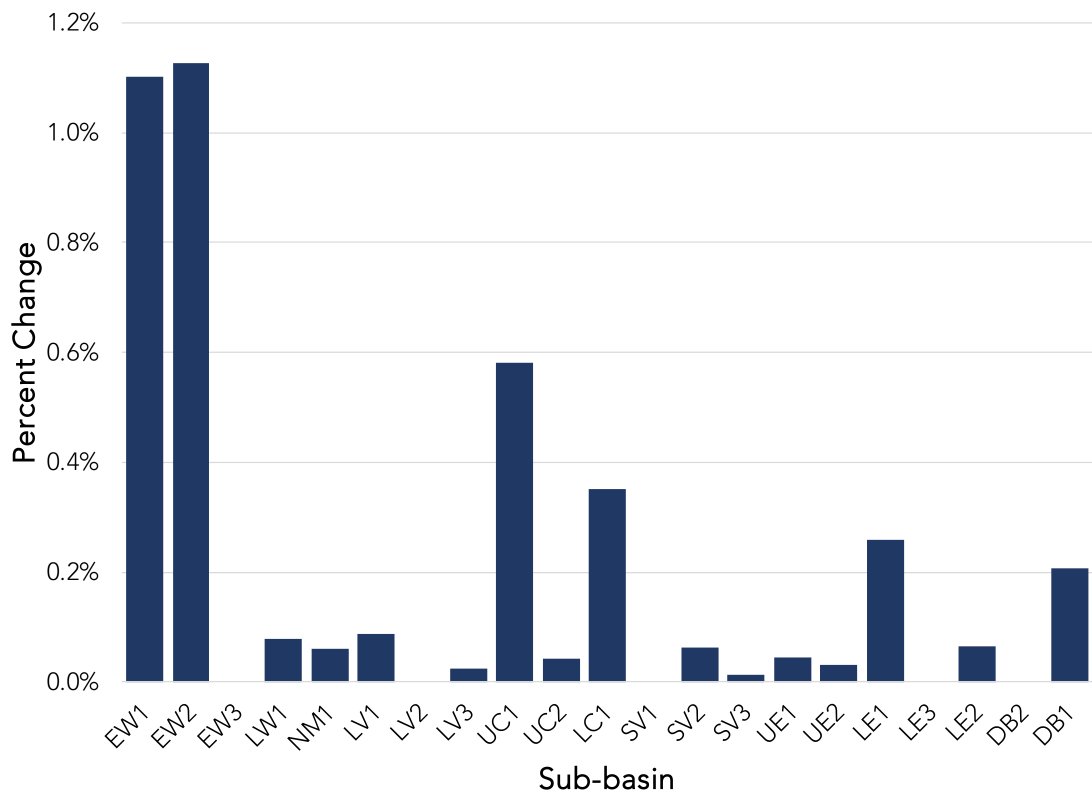

Figure 1.5.5 Change in percentage of public open space in the Delaware River Basin by sub-basin from 2010 to 2016.

1.5.5 Actions and Needs

Coordination among federal, regional, state, local and private/non-profit organizations through efforts such as the Delaware River Watershed Initiative (DRWI) is increasingly important as competing interests in how land is used among various watershed users and stakeholders becomes more intense.

As the pool of land available to develop (or conversely, to protect) shrinks, it becomes more important than ever to prioritize both where preservation efforts will occur and what measures will be implemented. Organizations such as the DRBC, the PDE, federal, state, and county governments, and local watershed and conservation organizations should coordinate more closely in their efforts to prioritize areas of focus, cultivate collaborative land protection projects, coordinate pursuits of funding opportunities, and support open sharing of data, information, and expertise.

1.5.6 Summary

Publicly accessible open space is an important component of overall watershed (and Basin) health. Currently, the Estuary portion of the Basin has about 12% of land protected and publicly accessible. The nontidal portion of the Basin has a proportion of land protected at approximately 18%, yielding an overall level of protected land of 15% in the Delaware River Basin.

Where open land is protected has a large bearing on local water quality and habitat value. Public access to these valuable resources has the benefit of both providing recreation to residents, and fostering a preservation ethic in the public imagination. Providing protection to land within watersheds leads to better outcomes in terms of water quality and quantity, watershed and aquatic habitat health, and well-being of the Basin's inhabitants.

Suggested Citation for this Chapter

Homsey, A., L. Haaf, K. Somers. 2017. "Chapter 1.5 - Public Open Space" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 57-63.

1.6 Public Access Points

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Reprinted from Partnership for the Delaware Estuary. 2012. Technical Report for the Delaware Estuary and Basin. P. Cole, A. Padeletti, D. Kreeger (eds). PDE Report No. 12-01. 255 pages.

1.6.1 Description of Indicator
Public access points are publicly and privately owned land adjacent to the Delaware River and Bay that provide entrance for boaters, fishermen, and water-borne recreational activities.

1.6.2 Present Status
The States of Delaware, New Jersey, New York, and Pennsylvania; U.S. National Park Service, and private marinas own 150 public access points along 330 miles of the Delaware River and Bay from the Catskill Mountains of New York down to Cape Henlopen, Delaware (Table 1.6.1). Access points are reported in river miles (RM; Fig 1.6.1). This translates to an average density of one access point for every 2 river miles.

1.6.3 Past Trends
No new access points have been added since the first inventory was completed in the 2012 Technical Report for the Delaware Estuary and Basin (those data are in Table 1.6.1).

1.6.4 Future Predictions
Federal, state, local, and nonprofit agencies will continue to acquire public access points along the Delaware River and Bay.

1.6.5 Actions and Needs
Public access points should be acquired to achieve a density of one site per mile compared to the present two sites per mile along the Delaware River and Bay. Gaps where public access sites should be acquired include:

Between RM 1 and 11 (Lewes to Cedar Creek)
Between RM 11 and 22 (Bowers Beach)
Between RM 29 and 41 (Woodland Beach)
Between RM 65 and 81 (Chester)
Between RM 138 and 147 (Lambertville)
Between RM 198 and 212 (Delaware Water Gap)
Between RM 315 and 322 (Long Eddy)

1.6.6 Summary
The States of Delaware, New Jersey, New York, and Pennsylvania, the U.S. National Park Service, and private marinas own 150 public access points along 330 miles of the Delaware River and Bay from Cape Henlopen, Delaware to the Catskill Mountains of New York. This translates to an average density of one access point for every two river miles.

Suggested Citation for this Chapter
Sanchez, J. R., G. Kauffman, K. Reavy, A. Homsey. 2012. "Chapter 1.6 - Public Access Points" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07 pp. 64-69.

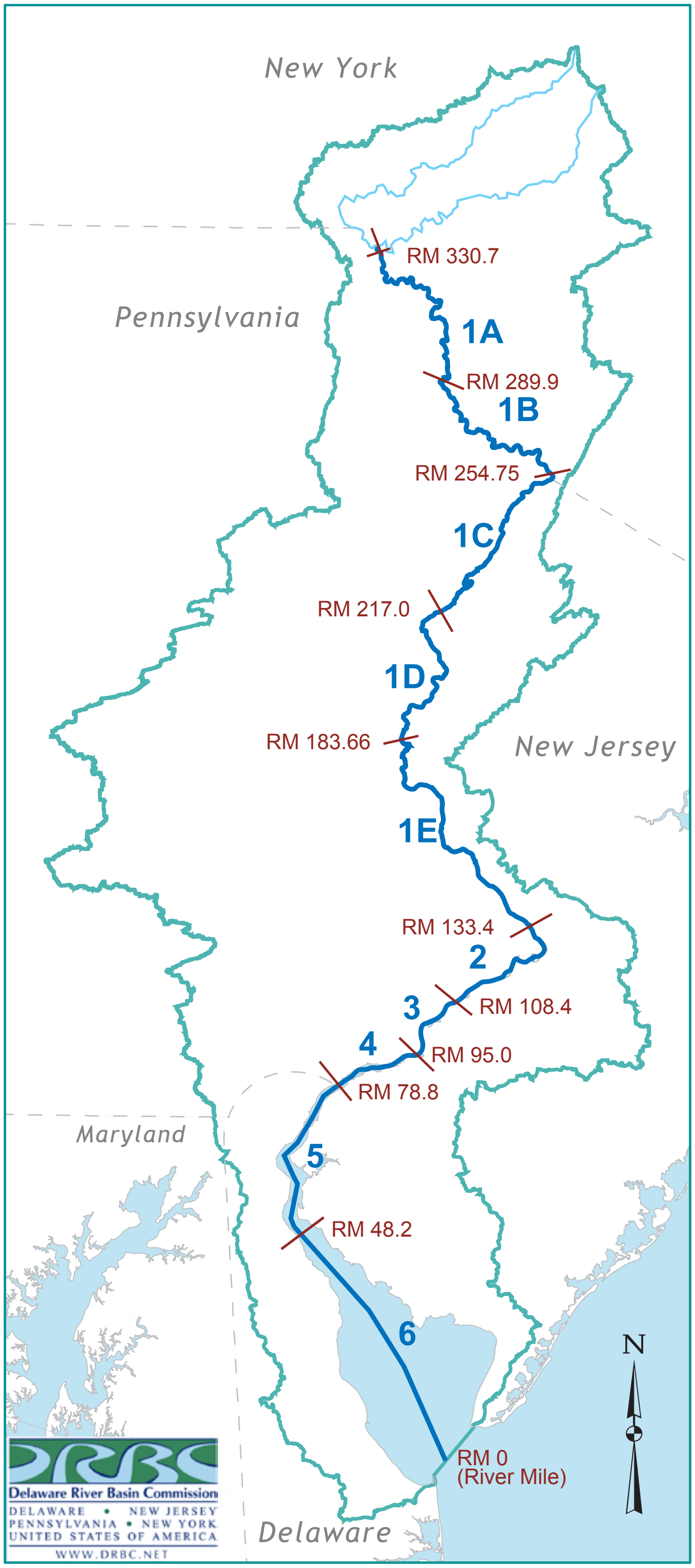

Figure 1.6.1 River Miles of the Delaware River and Bay as conventionalized by the Delaware River Basin Commission. Mileage begins (at RM=0) at the mouth of the Delaware Bay, in between Lewes, DE and Cape May, NJ.

Table 1.6.1 Delaware River and Bay public access points (see Fig 1.6.1 for river mile locations).

River Mile	Location	State	County
1	Lewes Wildlife Mgmt. Area (DNREC DFW)	DE	Sussex
11	Cedar Creek Wildlife Mgmt. Area (DNREC DFW)	DE	Sussex
22	Bowers Beach Wildlife Mgmt. Area (DNREC DFW)	DE	Kent
29	Port Mahon Wildlife Mgmt. Area (DNREC DFW)	DE	Kent
41	Woodland Beach Wildlife Mgmt. Area (DNREC DFW)	DE	New Castle
44	Woodland Beach - Duck Creek Wildlife Mgmt. Area (DNREC DFW)	DE	New Castle
45	Collins Beach Wildlife Mgmt. Area (DNREC DFW)	DE	New Castle
49	NJDFW Mad Horse Creek WMA Stow Neck Rd. Canton	NJ	Cumberland
55	Augustine Beach Wildlife Mgmt. Area (DNREC DFW)	DE	New Castle
58	Fort DuPont Wildlife Mgmt. Area (DNREC DFW)	DE	New Castle
59	Penn Salem Marina Rte. 49 Salem	NJ	Salem
65	Pennsville Municipal Boat Ramp Riviera Dr.	NJ	Salem
81	Bridgeport Boat Yard (Racoon Creek) 118 Ferry Lane	NJ	Gloucester
82	Chester Boat Ramp Commodore Barry Bridge	PA	Delaware
82	Chester City at Flower St.	PA	Delaware
86	Anchorage Marina	NJ	Gloucester
86	Lagoon Marina	NJ	Gloucester
91	RiverWinds Point, West Deptford Township	NJ	Gloucester
93	West Deptford Mun. Boat Ramp Center St.	NJ	Gloucester
93	West Deptford Township	NJ	Gloucester
94	Fort Mifflin	PA	Philadelphia
95	William Hargrove Marina	PA	Philadelphia
95	West Creek Westville	NJ	Gloucester
99	Piers Marina	PA	Philadelphia
99	Penn's Landing Corporation	PA	Philadelphia
99	Wiggins Park Camden	NJ	Camden
100	Pyne Point Marine Services 7th St. Camden	NJ	Camden
100	Philly Marine Center	PA	Philadelphia
104	NJDFW Pennsauken Boat Ramp Derousse Ave. Delair	NJ	Camden
105	Pennsauken	NJ	Camden
106	PFBC Frankford Arsenal Access 5600 Tacony St.	PA	Philadelphia
106	PFBC Frankford Arsenal	PA	Philadelphia
107	Palmyra Cove Nature Park	NJ	Burlington
108	PFBC Tacony Access Milner St.and Princeton Ave.	PA	Philadelphia
108	PFBC Tacony	PA	Philadelphia
110	Linden Ave at Pleasant Hill Park	PA	Philadelphia
110	Dredge Harbor Riverside	NJ	Burlington
110	Clarks Landing Marina	PA	Philadelphia

Table 1.6.1 con't

River Mile	Location	State	County
111	Lightening Jacks Marina 625 Harrison St. Riverside	NJ	Burlington
111	Philadelphia Boat Ramp Linden Ave.	PA	Philadelphia
111	Amico Island Riverside	NJ	Burlington
111	Lightning Jack's Marina	NJ	Burlington
111	Riverside Marina	NJ	Burlington
112	Hawks Island Marina 130 Rancocas Ave. Delanco	NJ	Burlington
112	Hawk Island Marina Delanco	NJ	Burlington
113	Station Avenue	PA	Philadelphia
115	Neshaminy State Park Marina	PA	Bucks
115	Three Seasons marina	PA	Bucks
116	Neshaminy State Park State Rd. and Cedar Ave. Bensalem	PA	Bucks
116	Neshaminy State Park	PA	Bucks
118	Curtin Marina E.Pearl Str. Burlington City	NJ	Burlington
118	Burlington City Boat Ramp Tathem Ave and Pearl St.	NJ	Burlington
118	Burlington	NJ	Burlington
118	Curtin Marina Burlington	NJ	Burlington
119	Bristol	PA	Bucks
122	D&S Boats and Marina Florence	NJ	Burlington
123	Florence	NJ	Burlington
128	Bordentown	NJ	Burlington
129	Bordentown Beach Park St.	NJ	Burlington
131	Trenton	NJ	Mercer
131	Ross Marina Trenton	NJ	Mercer
132	Trenton Waterfront Park	NJ	Mercer
133	Trenton Waterfront Park 1595 Lamberton Rd. off Rte. 29	NJ	Mercer
133	Welcome Park, Morrisville	PA	Bucks
133	W Mercer County's Roebling Park	NJ	Mercer
135	Ferry Road, Morrisville	PA	Bucks
138	PFBC Yardley Access Rte. 32, north end Yardley Boro.	PA	Bucks
147	Firemans Eddy Rte. 29, 1.8 mi. south Lambertville/New Hope Br.	NJ	Mercer
149	D&R Canal State Park Lambertville Bridge St.	NJ	Hunterdon
154	Virginia Forest Recreation Area Rte. 32	PA	Bucks
155	D&R Canal Park Byram Rte. 29, 3.4 mi. north of Stockton	NJ	Hunterdon
156	D&R Canal State Park Bulls Island Rec. Area	NJ	Hunterdon
163	Tinicim Park Rte. 32, Erwinna	PA	Bucks
164	NJDFW Ringwood Access Rte. 29, 1 mi. below Frenchtown	NJ	Hunterdon
168	PFBC Upper Black Eddy Access Rte. 32, below Milford Bridge	PA	Bucks
174	NJDFW Holland Church River Rd., 1 mi. south of Riegelsville bridge	NJ	Hunterdon
174	PFBC Reigelsville Access Rte. 611 north of Rte. 212	PA	Bucks

Table 1.6.1 con't

River Mile	Location	State	County
177	Frys Run Park Rte. 611, 6 mi. south of Easton	PA	Northampton
178	Theodore Roosevelt Recreation Area Rte. 611, 1 mi. south Raubsville	PA	Northampton
181	Wi-Hit-Tuk County Park Holmes Drive, 3 mi. south of Easton	PA	Northampton
183	Scott Park Boat Ramp Easton Rte. 611,mouth of Lehigh River	PA	Northampton
184	Phiilipsburg Boat Ramp Riverside Way, by free bridge	NJ	Warren
186	Northampton County Park Frost Hollow Rte. 611, 2.3 mi. north	PA	Northampton
189	Martins Creek PP&LRte. 611, 5.2 mi above Easton bridge	PA	Northampton
189	PFBC Sandts Eddy Access Rte.611, 5.2 mile above Easton bridge	PA	Northampton
197	NJDFW Belvidere Access Downstream from Belvidere bridge	NJ	Warren
198	Northampton Co. Park Doe Hollow River Rd. u.s. f Belvidere bridge	PA	Northampton
212	DWGNRA Kittatinny Beach Del. Water Gap below I-80 bridge	NJ	Warren
216	Worthington State Forest Old Mine Rd., 4 mi. north of I-80	NJ	Warren
218	DWGNRA Smithfield Beach River Rd.,3 mi.north of Shawnee	PA	Warren
220	DWGNRA Poxono Old Mine Rd., 8 mi. north of Del. Water Gap	NJ	Warren
222	DWGNRA Depew Old Mine Rd., 9.3 mi. north of Del. Water Gap	NJ	Warren
227	DWGNRA BushkillRte. 209, 1 mile north of Bushkill	PA	Pike
232	DWGNRA Eshback Rte. 209 mile markers 6 and 7	PA	Pike
239	DWGNRA Dingmans Ferry Toute 739 at Dingmans Bridge	PA	Pike
246	DWGNRA Milford Beach Rte. 209, 0.2 miles north of Rte. 206 bridge	PA	Pike
254	Tri-States Monument Pt. Jervis I-84 bridge	NY	Orange
255	West End Beach, Port Jervis	NY	Orange
258	Deerpark north of junction Routes 97 and 42. Sparrowbush	NY	Sullivan
258	UDSRRA DWGNRA Sparrowbush	NY	Sullivan
259	Sparrowbush	NY	Sullivan
260	Mongaup	NY	Sullivan
261	UDSRRA DWGNRA Mongaup Access	NY	Sullivan
267	Buckhorn Natural Area	PA	Sullivan
272	UDSRRA NPS Barryville Office	NY	Sullivan
273	National Park Service Barryville Office	NY	Sullivan
274	Highland. Route 97 1.5 miles west of Barryville.	NY	Sullivan
274	UDSRRA Highland	NY	Sullivan
277	UDSRRA Lackawaxen	PA	Wayne
278	Lackawaxen	PA	Wayne
278	Lackawaxen	PA	Wayne
282	Ten Mile River	NY	Sullivan
282	Highland	NY	Sullivan
282	Highland	NY	Sullivan
283	UDSRRA Ten Mile River	NY	Sullivan
290	Narrowsburg Race Course Road (Co Rte 24) to DeMauro Lane	NY	Sullivan

Table 1.6.1 con't

River Mile	Location	State	County
290	UDSRRA Narrowsburg, NY	NY	Sullivan
290	UDSRRA Narrowsburg, PA	PA	Wayne
290	Narrowburg,NY	NY	Sullivan
290	Narrowburg, PA	PA	Wayne
295	UDSRRA Skinners Falls	NY	Sullivan
296	Skinners Falls	NY	Sullivan
297	Milanville, PA	PA	Wayne
298	UDSRRA Damascus	PA	Wayne
299	Cochecton off Route 97 on Skinners Falls Road	NY	Sullivan
299	Damascus, PA	PA	Sullivan
304	Off Route 97 Callicoon,	NY	Sullivan
304	UDSRRA Callicoon, NY	NY	Sullivan
304	UDSRRA Callicoon, PA	PA	Wayne
304	Callicoon, NY	NY	Sullivan
304	Callicoon,PA	PA	Wayne
305	Kellams, Little Equinunk Creek	NY	Sullivan
310	Hankins	NY	Sullivan
311	UDSRRA River Est aamground	NY	Sullivan
312	Basket Creek at Basket Creek	NY	Sullivan
315	UDSRRA Long Eddy Access	NY	Sullivan
315	Long Eddy	NY	Sullivan
322	UDSRRA Lordville Access	NY	Delaware
323	Lordville	NY	Delaware
325	UDSRRA Buckingham Boat Access	NY	Delaware
325	Buckingham	PA	Wayne
330	Hancock Bard Parker Rd, south edge of Village off Rte. 97	NY	Delaware
330	UDSRRA Hancock Access	NY	Delaware
330	Hancock	NY	Delaware
W. Br.	Airport Rd. south edge of Deposit, ½ mi from Rte. 17	NY	Delaware
W. Br.	Hale Eddy Rte. 58 off Rte. 17, 6 ½ mi. west of Hancock	NY	Delaware
E. Br.	UDSRRA Balls Eddy Access	NY	Delaware

Abbreviations used in Table 1.6.1

New Jersey Division of Fish and Wildlife (NJDFW); Pennsylvania Fish and Boat Commission (PFBC); Delaware Water Gap National Recreation Area (DWGNRA); Upper Delaware River Scenic and Recreational Area (UDSRAR); DNREC Division of Fish and Wildlife (DFW); West Branch Delaware River (W. Br.); East Branch Delaware River (E. Br.)

1.7 Natural Capital Value

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Reprinted from Partnership for the Delaware Estuary. 2012. Technical Report for the Delaware Estuary and Basin. P. Cole, A. Padeletti, D. Kreeger (eds). PDE Report No. 12-01. 255 pages.

1.7.1 Description of Indicator

This section tabulates the economic value of the Delaware Estuary watershed as (1) market and non-market economic activity, (2) value of ecosystem goods and services, and (3) jobs and wages related to the watershed (Kauffman 2011).

1.7.2 Present Status

The natural resources of the Delaware Estuary watershed provide tremendous economic value through:

- The Delaware Estuary's water resources and habitats. Using economic activity as a measure of value, we find that the Delaware Estuary contributes over $10 billion in annual economic activity from recreation, water quality and supply, hunting and fishing, forests, agriculture and parks.
- The value of the goods and services provided by the Delaware Estuary's ecosystems. Using ecosystem goods and services as a measure of value, we find that the ecosystems of the Delaware Estuary provide $12 billion annually in goods and services in 2010 dollars*, with a net present value (NPV) of $392 billion calculated over a 100-year period.
- Employment related to the Delaware Estuary's water resources and habitats. Using employment as a measure of value, we find that the Delaware Estuary directly and indirectly supports over 500,000 [illegible] ally. This does not include the thousands or even millions of jobs in companies and industries that rely on waters of the Delaware Estuary for their industrial and commercial processes.

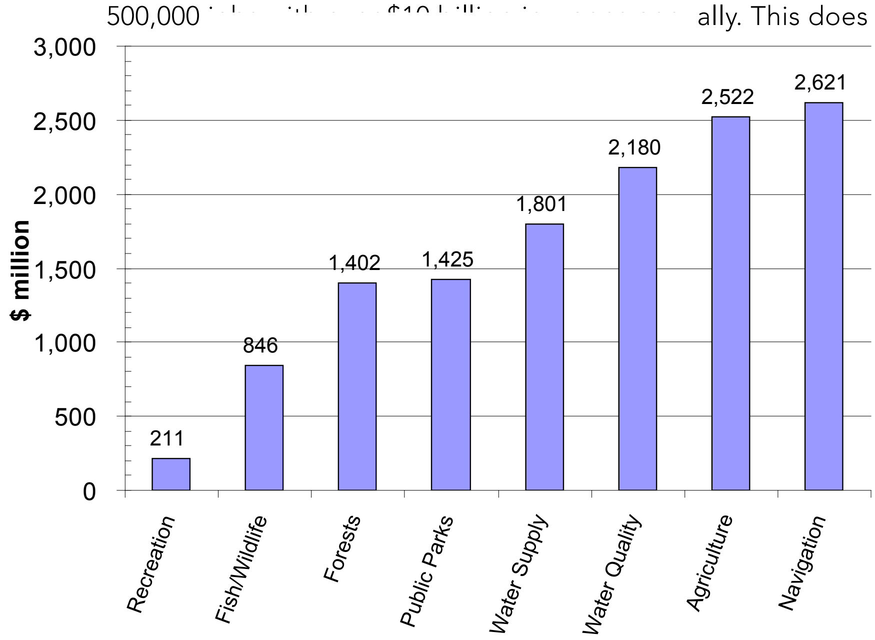

Figure 1.7.1 Annual economic value of the Delaware Estuary watershed.

Annual Economic Value

The Delaware Estuary watershed contributes over $10 billion in annual market and non-market value. Market value is determined by the sale/purchase of watershed goods such as drinking water, fish, or hunting supplies. Non-market value is provided by ecosystems such as pollution removal by forests, public willingness to pay for improved water quality, forest carbon

*$100 in 2010, as of May 2017, is worth $112.94 (https://data.bls.gov/cgi-bin/cpicalc.pl)

storage benefits, and health benefits of parks. Note that totals are rounded down to avoid double counting (Fig 1.7.1).

Ecosystem Services The Delaware Estuary watershed is rich in natural resources and habitat as measured by the economic value of ecosystem goods and services. Ecosystem goods are benefits provided by sale of watershed products such as drinking water and fish. Ecosystem services are economic benefits provided to society by nature such as water filtration, flood reduction, and carbon storage. The value of natural goods and services from ecosystems in the Delaware Estuary watershed is $12 billion (2010) with net present value (NPV) of $392 billion using a discount rate of 3% over 100 years (Table 1.7.1 and Table 1.7.2). Ecosystem services

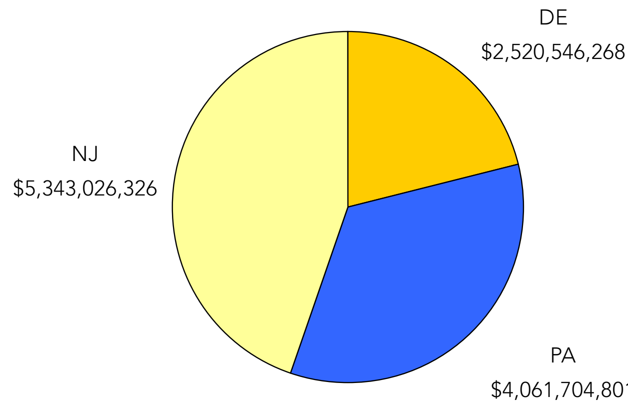

Figure 1.7.2 Ecosystem services value in the Delaware Estuary watershed by state.

Table 1.7.1 Ecosystem service value in the Delaware Estuary watershed by habitat type.

Ecosystem	Area (ac)	$/ac/yr 2010[1]	$/yr 2010	NPV $
Freshwater wetlands	317,213	13,621	4,320,647,087	140,421,030,319
Marine	16,588	10,006	165,982,947	5,394,445,767
Farmland	1,112,580	3,215[2]	3,577,486,604	116,268,314,632
Forest land	1,186,784	1,978	2,347,605,465	76,297,177,613
Saltwater wetland	145,765	7,235	1,054,617,851	34,275,080,170
Barren land	18,630	0	0	0
Urban	865,778	342	295,761,123	9,612,236,487
Beach/dune	900	48,644	43,758,633	1,422,155,566
Open water	131,388	1,946	255,655,983	8,308,819,443
Total	3,795,626	-	12,061,000,000	391,999,000,000

1. NJDEP 2007 [sic, 2004]; 2. USDA 2009

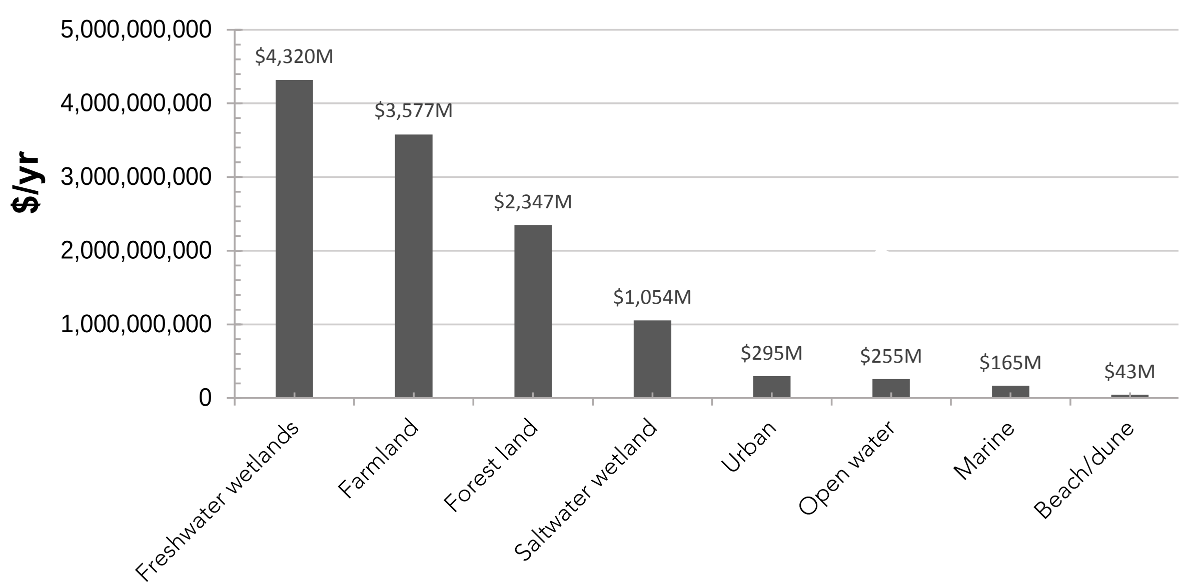

Figure 1.7.3 Ecosystem service value in the Delaware Estuary watershed by habitat type.

Table 1.7.2 Ecosystem goods and services value of the Delaware Estuary watershed.

Category	Goods and Services	Value (million $)
Water Quality	Water Treatment by Forests ($62/mgd)	17
	Wastewater Treatment ($4.00/1000 gal)	1,490
	Increased Property Value (+8% over 20 years)	13
	Willing to Pay for Clean Water ($38/nonuser-$121/user)	660
Water Supply	Drinking Water Supply ($4.78/1000 gal)	1,333
	Irrigation Water Supply ($300/ac-ft)	30
	Thermoelectric Power Water Supply ($44/ac-ft)	298
	Industrial Water Supply ($200/ac-ft)	140
Fish and Wildlife	Commercial Fish Landings ($0.60/lb)	34
	Fishing (11-18 trips/angler, $17-$53/trip)	334
	Hunting (16 trips/hunter, $16-50/trip)	171
	Wildlife/Bird-watching (8-13 trips/yr, $15-$27/trip)	306
	Crop, poultry, livestock value ($2,300/ac)	2,522
Maritime Transportation	Navigation ($15/ac-ft)	221
	Port Activity	2,400
Recreation	Swimming ($13.40/trip)	9
	Boating ($30/trip)	47
	Fishing ($62.79/trip)	52
	Wildlife/bird watching ($77.73/trip)	104
Forests	Carbon Storage ($827/ac)	981
	Carbon Sequestration ($29/ac)	34
	Air Pollution Removal ($266/ac)	316
	Building Energy Savings ($56/ac)	66
	Avoided Carbon Emissions ($3/ac)	4
Public Parks	Health Benefits ($9,734/ac)	1,057
	Community Cohesion ($2,383/ac)	259
	Stormwater Benefit ($921/ac)	100
	Air Pollution Control ($88/ac)	9
Total Value	**Economic Value**	**$ Million**
	Market Value	> 8 billion
	Non-Market Value	>2 billion

by state include Delaware ($2.5 billion, NPV $81.9 billion), New Jersey ($5.3 billion, NPV 173.6 billion), and Pennsylvania ($4.1 billion, NPV $132.0 billion)(Fig 1.7.2).

Jobs and Wages The Delaware Estuary watershed is a jobs engine that supports over 500,000 direct and indirect jobs with $10 billion in annual wages in the coastal, farm, ecotourism, water/wastewater, recreation, and port industries. Note total jobs and wages are rounded down to avoid double counting (Table 1.7.3; Fig 1.7.4; Table 1.7.4).

Jobs directly associated with the Delaware Estuary watershed (i.e. water/sewer construction, water utilities, fishing, recreation, tourism, and ports) employ 192,785 people with $4.3 billion in wages:

- Delaware (15,737 jobs, $340 million wages)
- New Jersey (52,007 jobs, $1.1 billion wages)
- Pennsylvania (125,041 jobs, $2.8 billion wages)

Jobs indirectly related to the waters of the Delaware Estuary watershed (based on multipliers of 2.2 for jobs and 1.8 for salaries) employ 231,342 people with $3.4 billion in wages in:

- Delaware (18,884 jobs, $270 million wages)
- New Jersey (62,408 jobs, $0.9 billion wages)
- Pennsylvania (150,049 jobs, $2.2 billion in wages)

The National Coastal Economy Program (Kildow et al. 2009) reports coastal employment in the Delaware Estuary watershed provides 44,658 jobs earning $947 million in wages in:

- Delaware (12,139 jobs, $214 million wages)
- New Jersey (4,423 jobs, $140 million wages)
- Pennsylvania (28,096 jobs, $593 wages).

Table 1.7.3 Jobs and wages related to the Delaware Estuary watershed.

Sector	Jobs	Wages ($ million)	Data Source
Direct Basin Related	192,785	4,280	U.S. Bureau of Labor Statistics (2009)
Indirect Basin Related	231,342	3,420	U.S. Census Bureau (2009)
Coastal	44,658	947	National Coastal Economics Program (20090
Farm	28,276	1,159	USDA Census of Agriculture (2007)
Fishing/Hunting/Birding	24,713	812	U.S. Fish and Wildlife Service (2008)
Water Supply Utilities	2,290	127	UDWRA and DRBC (2010)
Wastewater Utilities	1,021	51	UDWRA and DRBC (2010)
Watershed Organizations	150	8	UDWRA and DRBC (2010)
Port Jobs	12,121	772	Economy League of Greater Phila. (2008)
Delaware Estuary watershed	> 500,000	>$10 billion	-

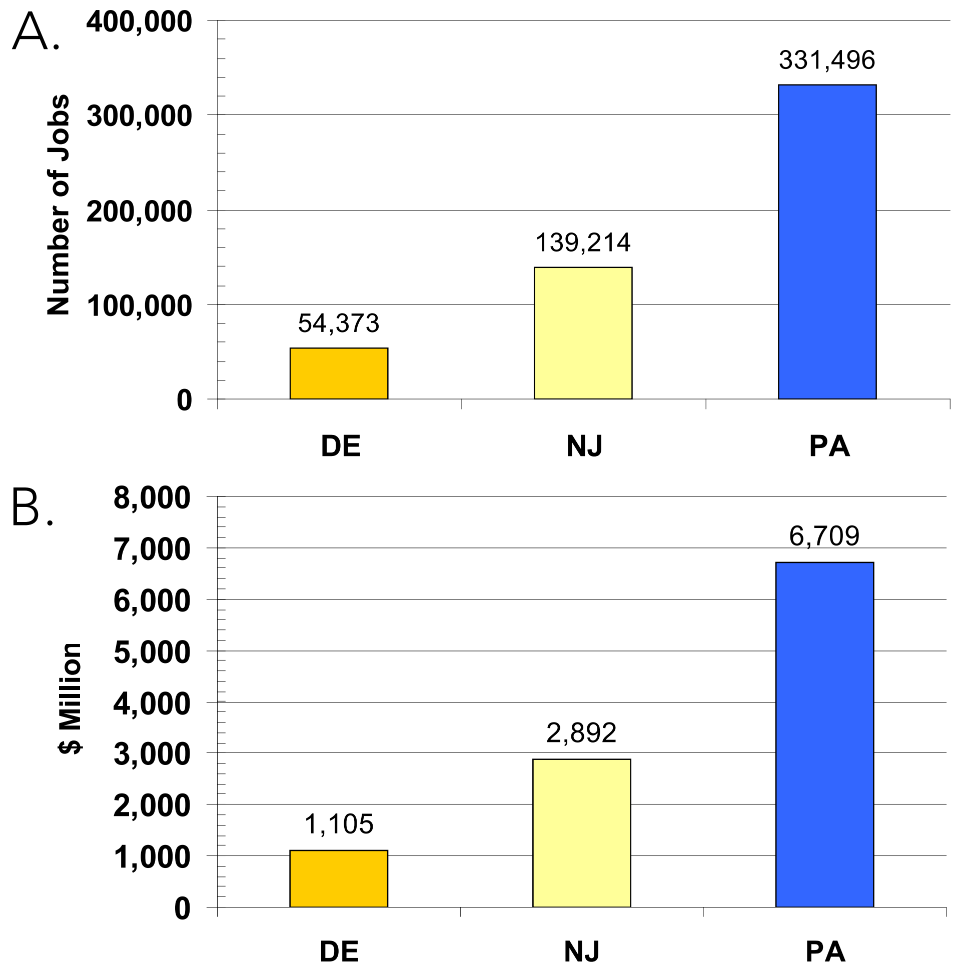

Figure 1.7.4 Jobs (A) and wages (B) related to the Delaware Estuary watershed by state.

Table 1.7.4 Jobs and wages in the Delaware Estuary watershed by state.

Sector	Jobs			Wages ($M)		
	DE	NJ	PA	DE	NJ	PA
Direct Basin Related	15,737	52,007	125,041	340	1,100	2,800
Indirect Basin Related	18,884	62,408	150,049	270	900	2,200
Coastal	12,139	4,423	28,096	214	140	593
Farm	3,289	8,287	16,700	135	340	685
Fishing/Hunting/Birding	4,092	11,365	9,256	134	373	304
Water Supply Utilities	126	509	1,654	7	28	92
Wastewater Utilities	106	215	700	5	11	35
Delaware Estuary watershed	54,373	139,214	331,496	1,105	2,892	6,709

1.7.3 Past Trends

Based on recent forest loss estimates from Chapter 1.3[‡], if the basin lost 31,471 acres from 1996-2006, then the loss in ecosystem services values for that period was $62 million over 100 years at $1,978 per acre.

1.7.4 Future Predictions

The economic value of the Delaware Estuary and Basin may increase with improved water quality and habitat.

1.7.5 Actions and Needs

Continued investment is needed to support the multi-billion dollar economic values of the Delaware Estuary and Basin.

1.7.6 Summary

The natural resources of the Delaware Estuary and Basin provide tremendous economic value such as (a) $10 billion in annual economic activity from recreation, water quality and supply, hunting and fishing, forest, agriculture, and parks; (b) ecosystem goods and services valued at $12 billion annually (in 2010); and (c) direct and indirect support of over 500,000 jobs with over $10 billion in annual wages.

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Suggested Citation for this Chapter

Sanchez, J. R., G. Kauffman, K. Reavy, A. Homsey. 2012. "Chapter 1.7 - Natural Capital Value" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07 pp. 70-75.

‡This is in reference to the 2012 TREB report;

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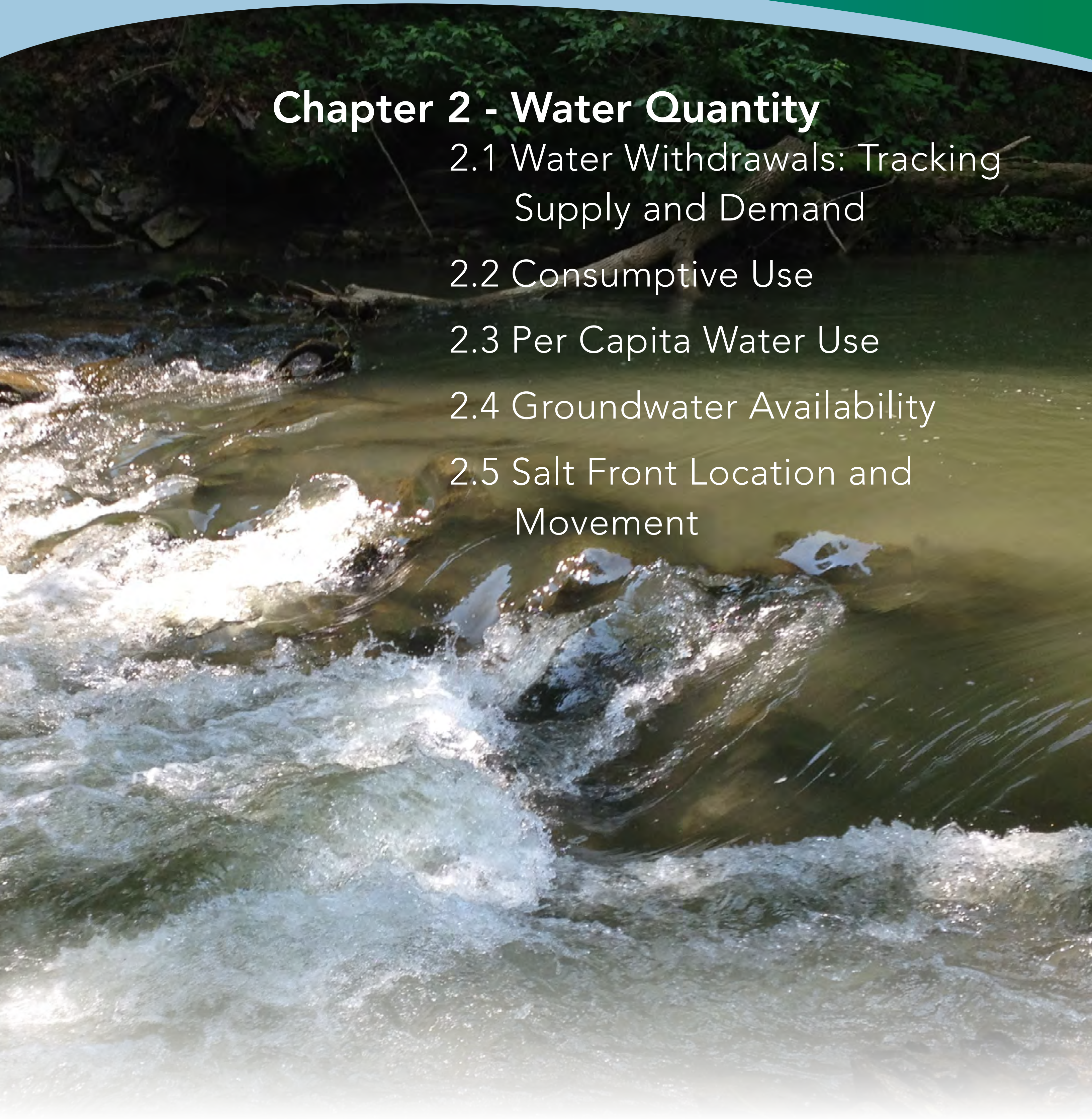

Chapter 2 - Water Quantity

2.1 Water Withdrawals: Tracking Supply and Demand

2.2 Consumptive Use

2.3 Per Capita Water Use

2.4 Groundwater Availability

2.5 Salt Front Location and Movement

Partnership for the DELAWARE ESTUARY

December, 2017 | Report No.17-07

A publication of the Partnership for the Delaware Estuary—A National Estuary Program

2. Water Quantity

J. Kent Barr
Delaware River Basin Commission

2.1 Water Withdrawals: Tracking Water Supply and Demand

2.1.1 Description of Indicator

Water withdrawals are tracked to identify key water-using sectors and trends. Accurate and comprehensive water use information enables the proper assessment, planning and management of water resources. As reporting improves, so does our accounting and understanding of the need for water among various water-using sectors. As noted above, 2014 water withdrawal data were compiled to generate a Basin-wide and regional assessment by water use sector. All data are based on withdrawals reported to state agencies except for data for the Self-supplied Domestic (individual homeowner wells) sector. Self-supplied domestic use was estimated based on the population from Census 2010 data for populations that reside outside of public water system (PWS) service areas. An estimated use of 75 gallons/capita/day, based on USGS estimates was applied to calculate water use by this sector.

Total water withdrawals from the Delaware River Basin Upper and Central regions, and the Lower and Bay regions, based on calendar year 2014 data are displayed in Figures 2.1.1, 2.1.2, and 2.1.3 respectively.

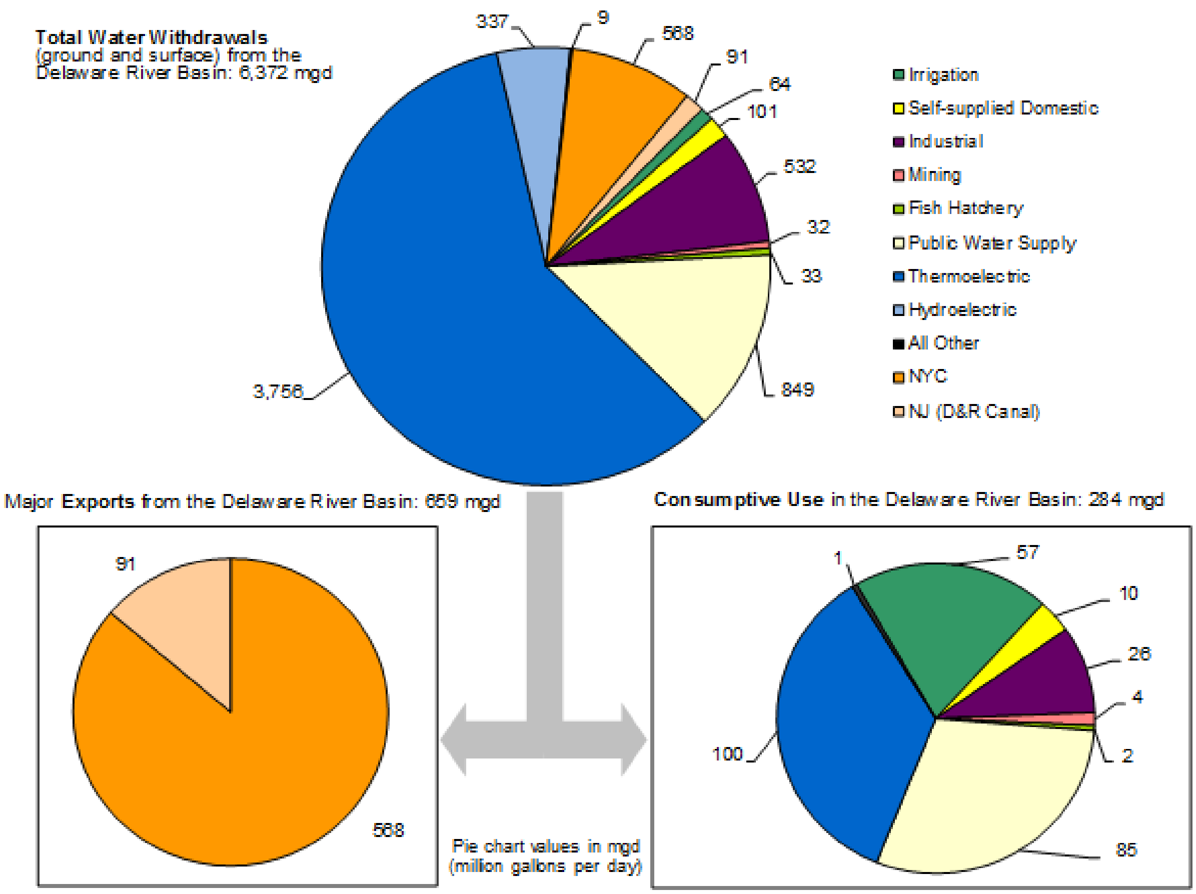

Figure 2.1.1 Total water withdrawals from the Delaware River Basin, 2014 in mgd (million gallons per day).

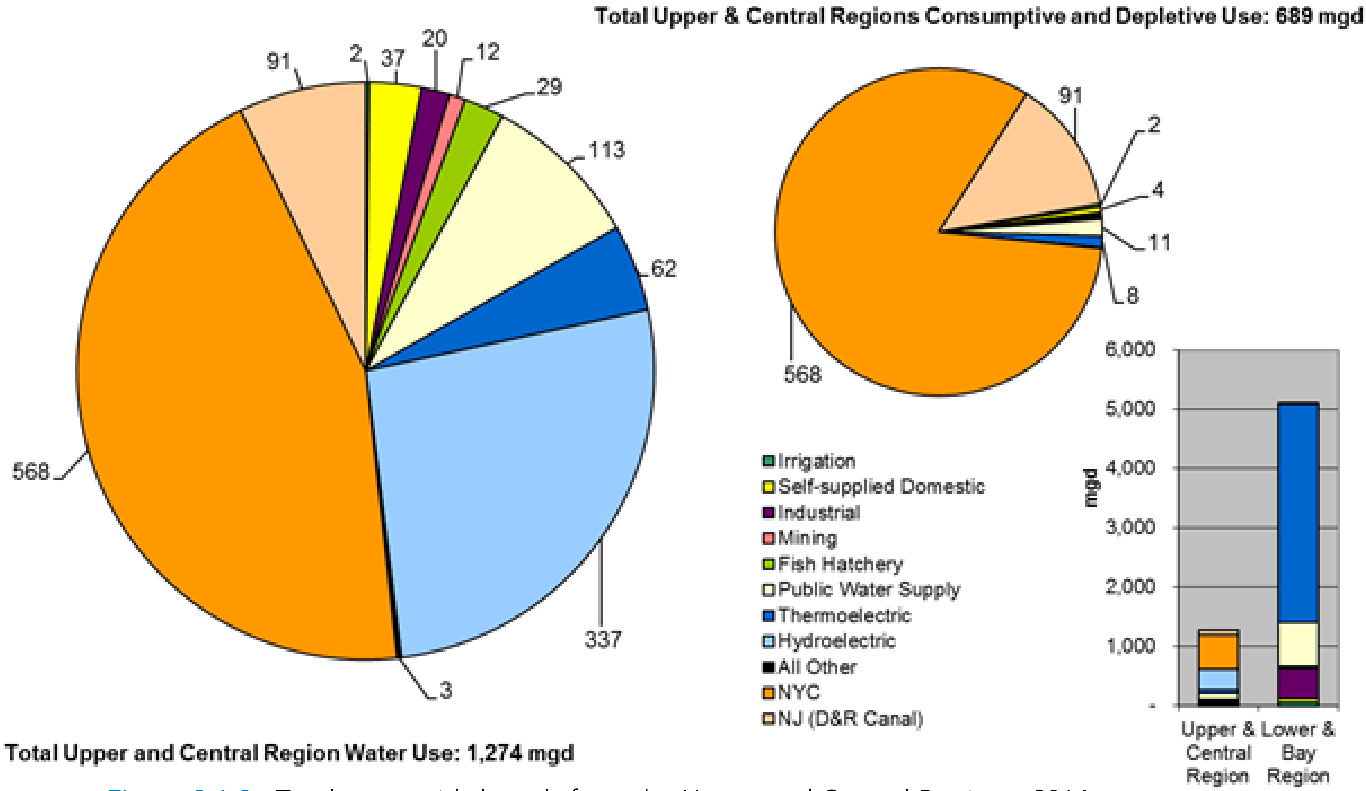

Figure 2.1.2 Total water withdrawals from the Upper and Central Regions, 2014.

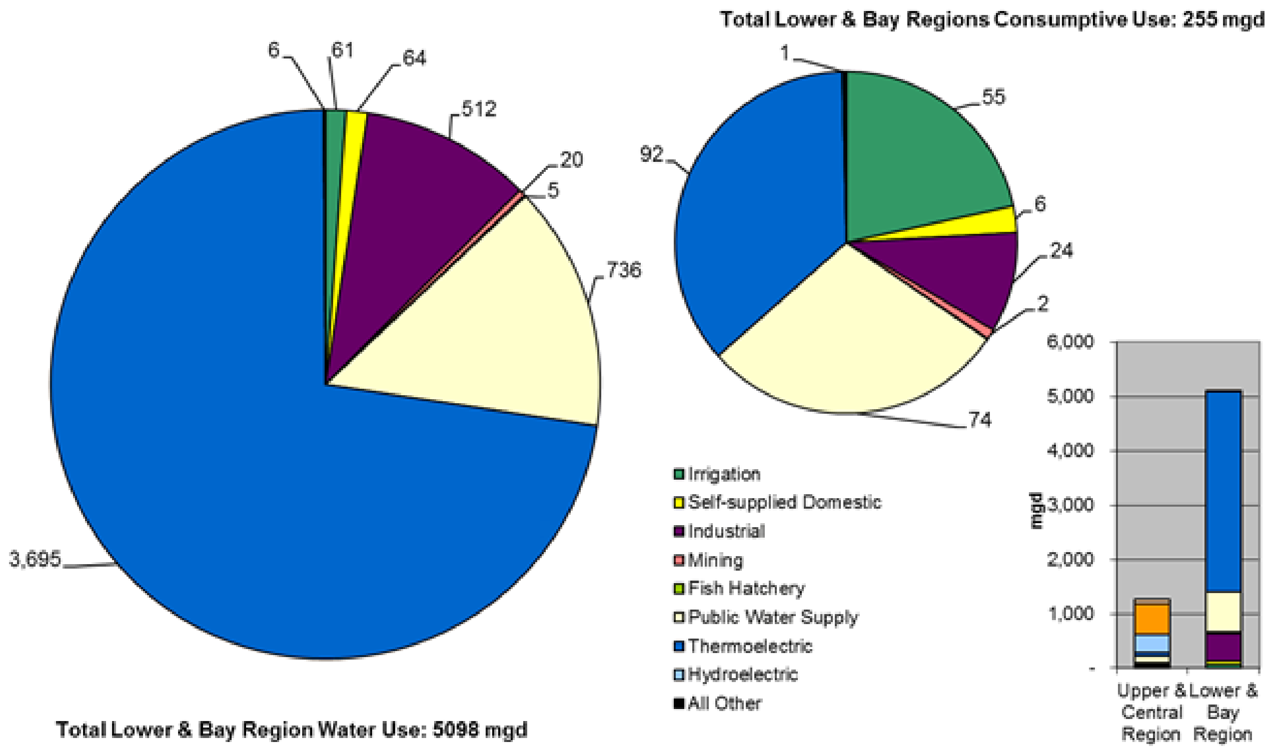

Figure 2.1.3 Total water withdrawals from the Lower and Bay Regions, 2014.

2.1.2 Present Status

Approximately 15 million people rely on water from the Delaware River Basin for their water needs. On average, over 6 billion gallons of Delaware River Basin water are used each day. This includes an average of approximately 570 million gallons per day (mgd) for populations in New York City and 90 mgd for northeastern New Jersey, which combined account for around 10% of total water withdrawals from the Basin. A system of reservoirs in the Upper Basin store water for export to New York City and make compensating releases to maintain downstream water temperatures and flows. New Jersey exports water from the Basin via the Delaware and Raritan Canal which draws from the mainstem Delaware River in Hunterdon County, NJ.

Within the Basin, uses related to power generation (thermoelectric) account for the majority of water withdrawals (59%) with the next largest use for public water supplies (13%). However, in managing water resources, the withdrawal volume may not be as important as where and when the water is returned to the system. Water not immediately returned is considered consumptive use (see Chapter 2.2 - Consumptive Use).

2.1.3 Past Trends

Over the past two decades the New York City diversion has decreased due in large parts to water conservation efforts. A long term chart of water exported from the Basin to meet New York City needs is shown in Figure 2.1.4. A five-period moving average was included on the chart to smooth the impact of short term fluctuations in water demand and the influence of weather patterns.

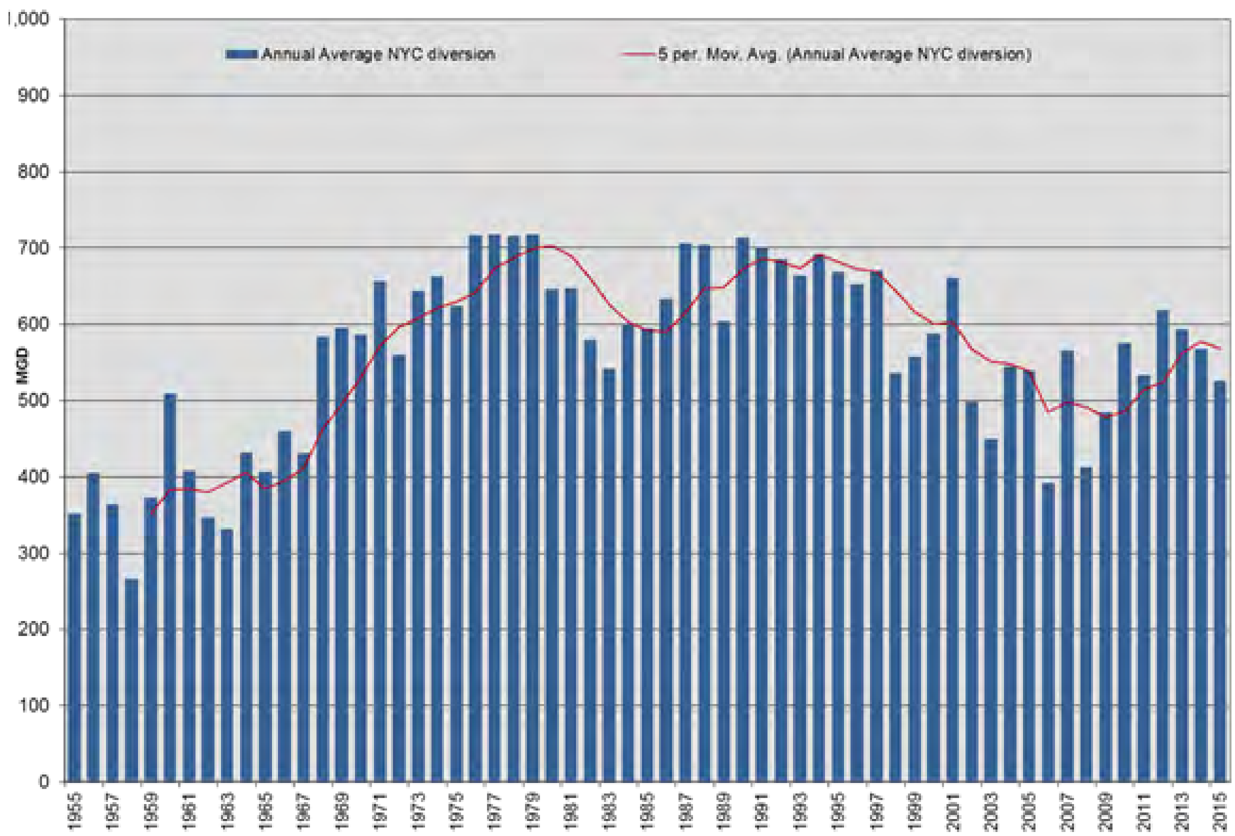

Figure 2.1.4 Water exported to New York City from Delaware River Basin 1955 - 2015 (Annual Data).

2.1.4 Future Predictions

Understanding water withdrawals, water use, and supply is integral to the management of water resources. In recent years, understanding the ways in which water is withdrawn and used has improved greatly, as have the underlying systems in place to manage the data. This has led to more timely and comprehensive assessments.

Key Delaware River Basin water use facts:

- Total ground and surface water withdrawals from the Basin: 6,372 mgd (6.4 billion gallons per day);
- Major Exports from the Basin: 659 mgd;
- Consumptive Use in the Basin: 284 mgd;
- Over 90% of all water used in the Basin is obtained from surface waters
- Three dominant use sectors account for approximately 80% of total water withdrawals; these sectors are: power generation (Thermoelectric, 59%), public water supply (PWS, 13%), and industrial use (Industry, 8%).

DRBC tracks withdrawals and water use in these three dominant water using sectors closely. Currently, data for these key sectors extend through calendar year 2014 and provide a monthly time series spanning a period of over 20 years. Although Figures 2.1.5 and 2.1.6 contain some data gaps, an overall pattern and trend in water withdrawals and consumptive use is apparent. The public water supply and industrial sectors display decreasing trends in total water withdrawn as well as consumptively used. Downward trends in withdrawals for public water supply are primarily attributed to the influence of conservation practices, while downward trends in industrial use are more likely the result of facilities exiting the industrial sector through closure or relocation outside the Basin. The thermoelectric sector displays an overall decreasing trend in total water withdrawals, but increases in consumptive use. This is attributed to the increasing use of cooling towers as opposed to once through cooling for new or upgraded facilities. It is anticipated that these trends will continue, although the rate at which they occur may change over time.

2.1.5 Actions and Needs

Reporting of water withdrawals has improved in recent years due to electronic, web-based reporting, although state agencies are adopting this approach at different speeds so data improvements should continue. Additional studies of the potential growth in water demand for the thermoelectric sector is required due to the impact that large power generating facilities can have on water resources. Also, advances in quantifying the instream needs of aquatic ecosystems are necessary for achieving a balance between instream and offstream (withdrawal) water needs.

2.1.6 Summary

Recent advances in the collection and reporting of water withdrawals, primarily by state agencies, have improved our understanding of water use in the Delaware River Basin and its watersheds. The public water supply and industrial sectors display decreasing trends in total water withdrawn as well as consumptive use. The thermoelectric sector displays an overall decreasing trend in total water withdrawals, but increases in consumptive use, which are likely to continue. Major exports to supply portions of New York City have declined over the last few decades, but this trend may not continue, and annual exports may plateau in future years.

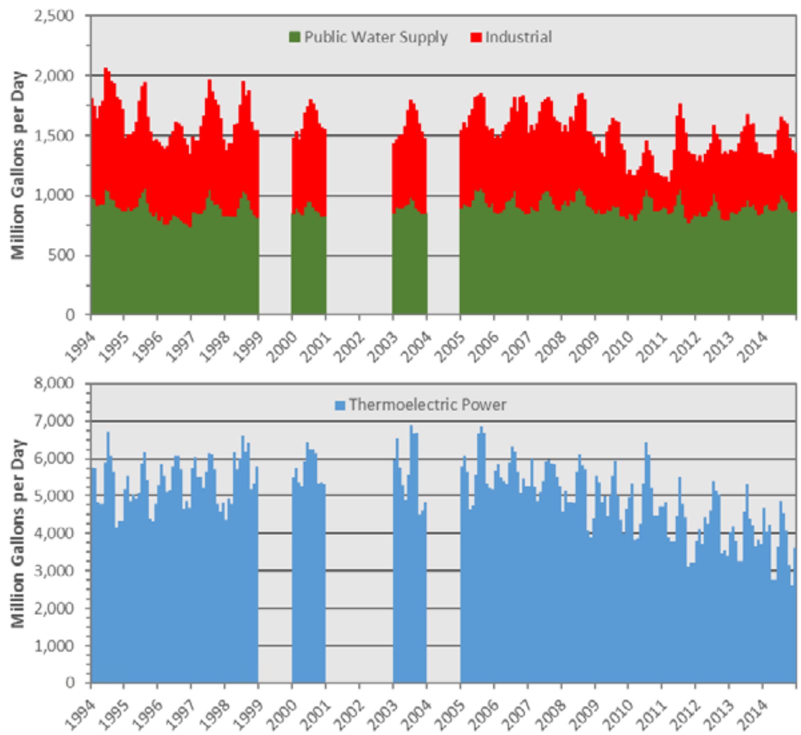

Figure 2.1.5 Monthly water withdrawals for three key sectors in the Delaware River Basin. (Note that no data are shown for months where data were incomplete to avoid visually skewing the trends).

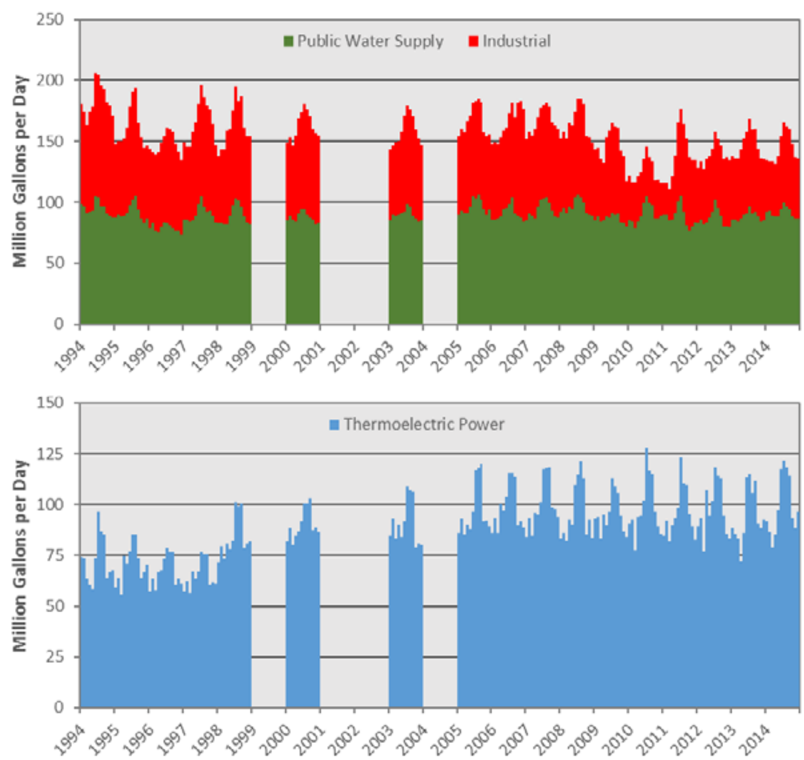

Figure 2.1.6 Monthly consumptive water use for three key sectors in the Delaware River Basin. (Note that no data are shown for months where data were incomplete to avoid visually skewing the trends).

2.2 Consumptive Use

2.2.1 Description of Indicator

Consumptive use is the portion of water withdrawn from the watershed and that is not immediately returned to the watershed. Section 1 described water withdrawals in the Delaware River Basin and Regions; however, a more important consideration in managing water resources is the amount of water consumed. Different types of water use vary in their consumptive withdrawls. For example, irrigation is highly consumptive (an estimate of 90% or greater is often used) as the water is absorbed by the plant or soil or lost to evaporation, while public water supplies (PWS) are typically considered to have a low consumptive use (~10%), as only a small portion of water used in homes and cities is not returned to the hydrologic system via sewerage systems. Another factor that influences consumptive use from a watershed perspective is the location of the withdrawal and discharge points. A PWS system that withdraws from a watershed but discharges the associated wastewater to a different watershed is 100% relative consumptive to the watershed from which it withdraws water. These types of issues need to be considered in a detailed water budget analysis. For the purposes of this report, sector-specific consumptive use factors were typically applied. However, for the power generation industry, which has highly variable consumptive use due to variability in cooling processes and industrial uses over 1 mgd, site-specific consumptive use factors were applied based on emperical data to increase the accuracy of the estimate.

2.2.2 Present Status

Figure 2.2.1 shows that the power generation and PWS sectors account for approximately 35% and 30%, respectively, of consumptive use in the Delaware River Basin and the Delaware Estuary. Agriculture and other irrigation-related uses (golf courses, nurseries) account for approximately another 20% of in-basin consumptive use. It should be noted that there are two major Basin exports to New York City and northern New Jersey, which can also be considered as consumptive uses and these two combined exports are twice the volume of all in-basin consumptive use. These exports were established as part of the 1954 Supreme Court Decree and are managed separately from other withdrawals and discharges in the Basin.

2.2.3 Past Trends

Consumptive use for the two largest sectors in the Delaware River Basin and Estuary have diverged in recent years. Consumptive use for PWS systems has remained relatively flat, most likely as a result of water conservation efforts. Figure 2.2.1 shows total consumptive water use (estimated at 10% of PWS withdrawals) for the PWS systems in the Delaware River Basin. Each data point represents a monthly consumptive use value and a linear trendline has been fitted to the data. The reason consumptive use has not followed increases in population has been driven by changes in plumbing codes, enacted in the early 1990s, which made plumbing fixtures and fittings more efficient. In addition, education and awareness of water conservation practices have played a role in decreasing water use for this sector despite increases in population (shown by the red line in Fig 2.2.1). However, it should be noted that water withdrawals, and therefore consumptive use, may have increased in some systems where there are population growth hot-spots and where water conservation practices cannot offset the more rapid increase in population.

Gaps in the data of Figure 2.2.1 indicate periods when one or more state agencies did not collect records, or could not prepare a database of water withdrawals. These data gaps provide challenges in creating a comprehensive dataset for the Delaware River Basin; the introduction of web-based reporting processes for collecting water withdrawal and use information should lead to more comprehensive and timely datasets.

Consumptive use for power generation has gone up in the past twenty years (see Fig 2.2.2 which shows monthly consumptive use values for the power sector and a 12 month moving average). Water withdrawals for thermoelectric power generation are primarily used for cooling purposes. The cooling process is typically achieved by either highly evaporative cooling towers or a once-through cooling process that uses a condenser to absorb heat. The two types of cooling use water in different ways. Evaporative cooling towers require a smaller volume of withdrawal but consume the majority of the water (>90% consumptive use). Once-through cooling requires a much greater availability of water but the rate of loss to evaporation is very small (typically <1%). The need for energy production in the Basin continues to increase and other (smaller) facilities have come online to meet demand. The new facilities use evaporative cooling, which withdraws a lesser volume but evaporates a greater percentage of the withdrawal.

The monthly data shown in Figures 2.2.1 and 2.2.2 highlight the extent to which water withdrawals and consumptive use vary seasonally. Thermoelectric power generation experiences peaks in the summer months that are related to the increased power demand for residential and commercial cooling. Simultaneously, public water suppliers experience peak demands in the summer months when lawn watering and other outside uses are greatest.

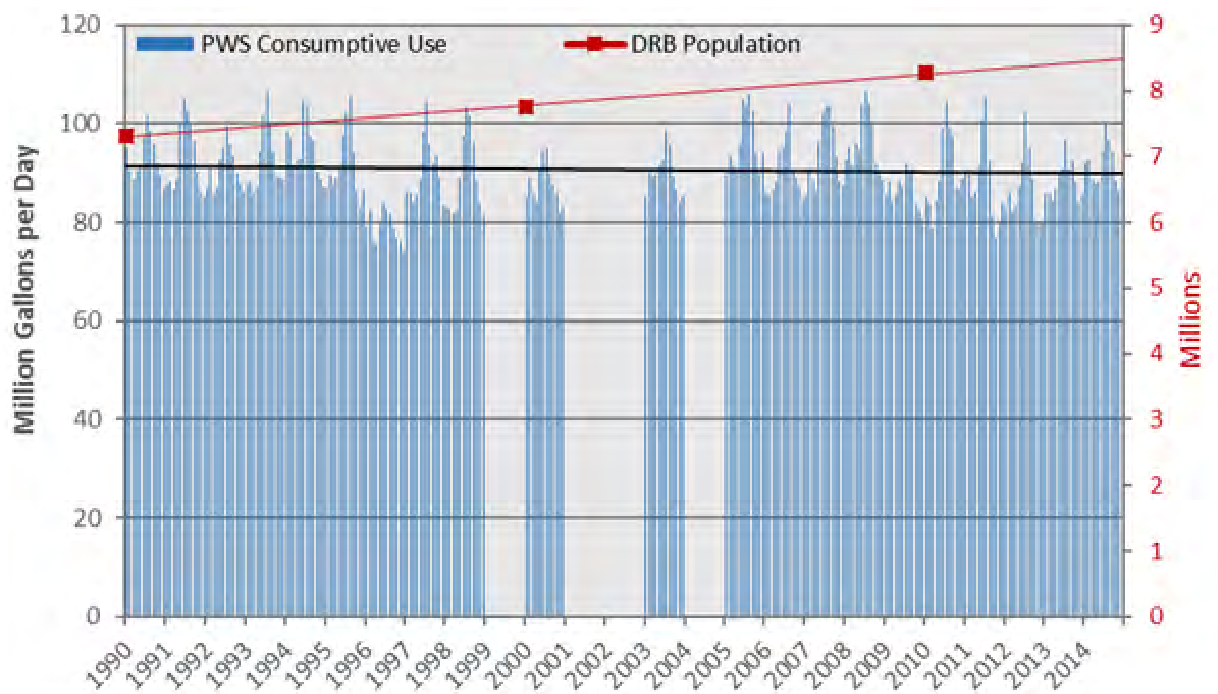

Figure 2.2.1 Trends in consumptive water use for public water supply.

2.2.4 Future Predictions

Consumptive use trends of the past two decades are expected to continue with respect to both the public water supply sector and the thermoelectric power sector. Most new thermoelectric power facilities will rely on cooling towers, which will result in greater levels of consumptive use for the sector overall. PWS withdrawals and corresponding consumptive use will likely continue to decline slightly as conservation initiatives continue to result in more efficient use of water for public supply. Additionally, detailed water auditing by public water suppliers will likely reduce overall withdrawal volumes and, thus, overall consumptive use for public water supply.

In 2009, DRBC amended its Comprehensive Plan and Water Code to implement an updated water audit approach to identify and manage water loss in the Basin. The purpose of the water audit is to track how effectively water is moved from its source to customers' taps and to ensure that public water supply systems quantify and address water losses. Approximately 6.7 million customers (80% of Basin residents) obtain

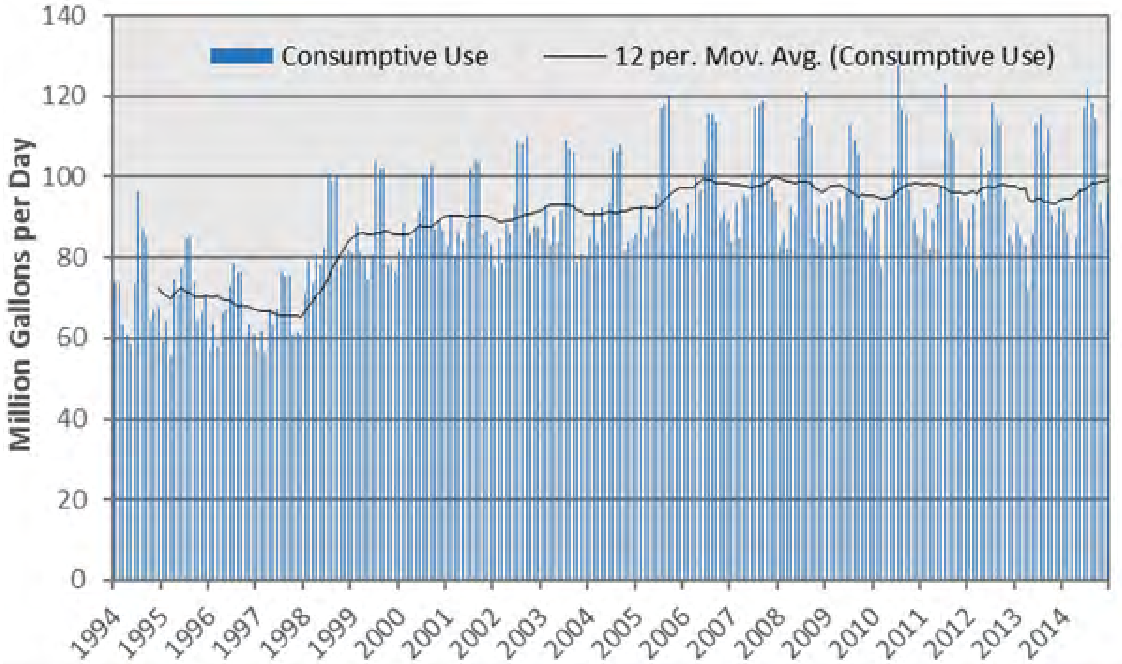

Figure 2.2.2 Trends in consumptive water use for thermoelectric power generation: aggregate consumptive demand for all systems in the Delaware River Basin.

their drinking water supply from public water supply systems. It is anticipated that significant reductions in water losses can be realized through this program. This will allow system operators, utility managers, and regulators to more effectively target their efforts to improve water supply efficiency, saving both water resources and money.

2.2.5 Actions and Needs

An accurate consumptive use characterization for a watershed requires a detailed analysis of each water use sector to determine accurate consumptive use factors representing site specific conditions. For example, at a small watershed scale, the simple assumption of 10% consumptive use for a PWS system that withdraws from the watershed but discharges wastewater outside the watershed would be inaccurate. This would need to be modeled as 100% consumptive, or as an export from the sending watershed and an import of wastewater (minus the 10% consumptive use) to the receiving watershed. More detailed tracking models that link withdrawal volumes more explicitly to discharge volumes are being applied in the Delaware River Basin, such as by New Jersey Geologic Survey's Water Transfer Data System and through the State Water Plan process in Pennsylvania.

2.2.6 Summary

An understanding of consumptive water use provides additional insight into water use patterns and is an important indicator in the management of water resources. Within the Delaware River Basin, the largest consumptive uses are from the thermoelectric, public water supply and agricultural water use sectors, accounting for approximately 85% of in-basin consumptive use. Slightly downward consumptive use trends are expected to continue in the public water supply sector while slightly upward trends may continue in the thermoelectric power sector. There are also two significant exports (to NYC and northern NJ) from the Delaware River Basin as shown in Figure 2.1.1, which can also be considered consumptive uses. These exports are expected to be relatively constant over time.

2.3 Per Capita Water Use

2.3.1 Description of Indicator

In managing water resources, it can be useful to have a metric for water use efficiency. One popular metric is per capita water use. This metric normalizes household water use for a given population. For the purposes of this report, per capita water use has been calculated as follows:

(Self supplied domestic water use+Public Water Supply) / Population

The above calculation excludes, where possible, water use by other sectors, such as power generation, which would skew any calculations. However, inclusion of some sectors could not be avoided because many public water supply systems provide water to a significant non-residential customer base (i.e., industrial or commercial customers). This use could not be separated out and may result in a higher per capita water use estimate in some regions. PWS service areas cover approximately 21% of the Delaware River Basin by area, but serve water to approximately 82% of the Basin's population (Fig 2.3.2).

Per capita water use was calculated basin wide, and for individual regional watersheds (Fig 2.3.1). For the per capita water use calculations by region, not all transfers across watershed boundaries could be accounted for. Although the data were adjusted to account for the impact of the largest of these watershed transfers across sub-basin boundaries (Point Pleasant, PA diversion and NJ Delaware & Raritan Canal), some transfers could not be accounted for and may skew per capita water use comparisons between regions. For instance, some PWS water withdrawals are in one sub-basin, and the PWS service area is in a different sub-basin. Several of the largest service areas in the Delaware River Basin cross watershed boundaries, even at the sub-region watershed scale (Fig 2.3.2). These water accounting issues exemplify the limitations of the per capita water use as an indicator for water resource management. Yet as long as these assumptions are acknowledged, per capita water use can be used as a limited measure of water use efficiency.

2.3.2 Present Status

Average per capita use in the Delaware River Basin is 112 gallons per capita per day (gpcd) and ranges from 80 gpcd to 181 gpcd across the ten sub-basins. Figure 2.3.1 shows Regional Per Capita Water Use for the eight sub-basins. Average per capita water use is greater in the Lower and Bay Regions (114 gpcd) than in the Upper and Central Regions (103 gpcd). The Schuylkill Valley sub-basin shows the highest per capita water use at 181 gpcd. Suburban areas (such as the Schuylkill sub-basin) with numerous residential developments and large lot-sizes would be expected to have a higher per capita use than heavily urbanized or rural areas.

2.3.3 Past Trends

A detailed trend analysis is not available, however a previous study based on 2003 data estimated average Basin-wide per capita water use at 133 gpcd with a range between 90 and 190 gpcd. Generally, per capita water use has decreased which is consistent with the trends shown in Figure 2.2.1 which shows a decrease in public water supply withdrawals, despite increases in population.

2.3.4 Future Predictions

Per capita water use is expected to continue to decline, because of increased water use efficiency, assuming the successes of water conservation strategies continue. Changes in plumbing fixtures and fittings, which went into effect 20 years ago, have led to greater water use efficiency. New construction has included more efficient plumbing and older homes have been retrofitted with more efficient appliances. Most of the benefit gained from these efficiencies may have already been realized; without additional effort and technical advances, water use efficiency and per capita use will eventually level off. Consequently, water withdrawals and consumptive use (see Chapter 2.3.1 and Chapter 2.3.2) may increase in response to growing population.

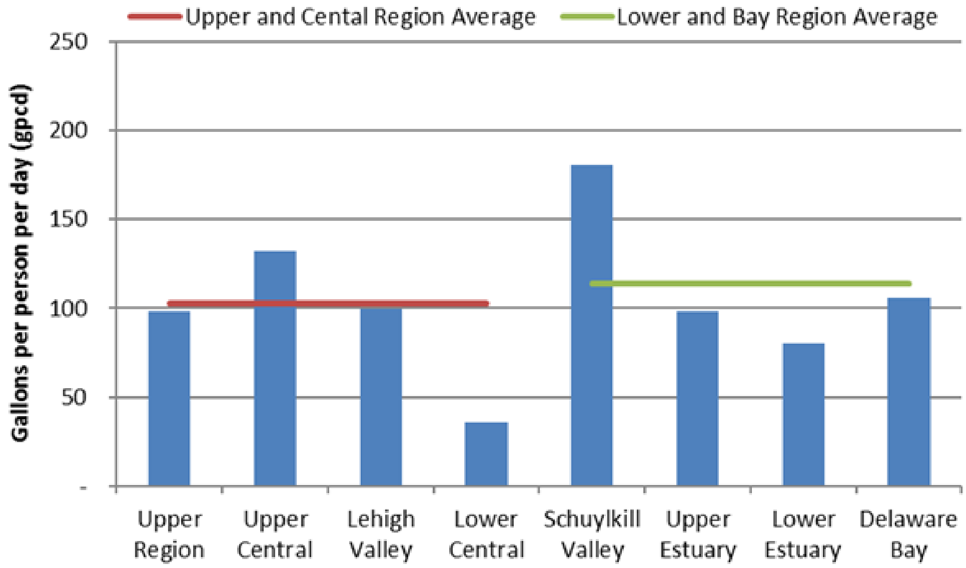

Figure 2.3.1 Regional per capita water use.

One way to further increase water efficiency would be to improve the condition and operation of water distribution infrastructure, which may be needed in many areas. In some areas, as much as 50% of the water put into distribution systems never reaches the customer as it is lost to leaky infrastructure or poor accounting practices by the water purveyor; hence there is great potential to increase water efficiency by focusing attention in this area. Increasing water efficiency could lead to decreased water demand and decreased withdrawals, which would result in cost savings for water purveyors in the form of a reduced need for system expansion. Increased completion of detailed water audits of public water supply systems (a DRBC requirement in the Delaware River Basin) will likely enable suppliers to better target capital improvements to old systems and may reduce overall water withdrawals and consumptive uses.

2.3.5 Actions and Needs

To improve the accuracy of per capita water use estimates, a detailed water use tracking model, such as that developed by the New Jersey Geological Survey, could be used to account for watershed transfers and link water withdrawals to the population with greater accuracy. Such a model is highly data intensive and would require a significant commitment of resources to compile and keep updated. However, the use of such a model, particularly in urbanized areas of the Delaware River Basin that have complex water distribution infrastructure and regional approaches to water supply management, would provide a greater understanding of how water is transfered and consumed within the watershed. Another measure to improve the accuracy and uniformity of the per capita consumption indicator would be to identify and report on PWS water use by customer type (e.g. residential, etc.).

2.3.6 Summary

Per capita consumption can provide an indication of water use efficiency over time and between different regions. The indicator needs to be interpreted carefully, as described above. Areas of above-average per capita water consumption may be a result of anomalous data and/or may represent an area where improved water conservation (e.g., through incentive programs) could lead to a reduction in water demand and increased water use efficiency.

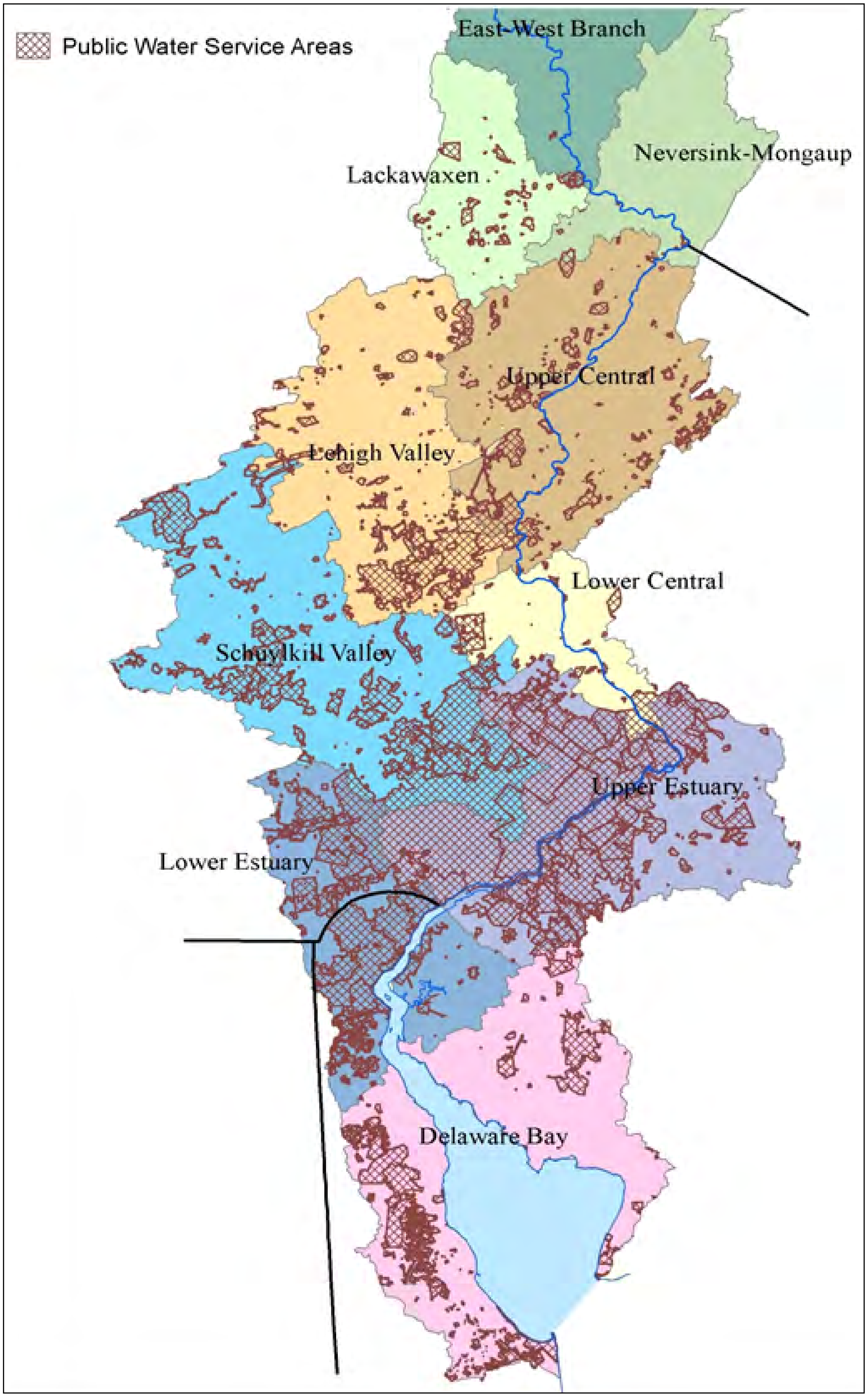

Figure 2.3.2 Public water supply service area coverage in the Delaware River Basin.

2.4 Groundwater Availability

2.4.1 Description of Indicator

Stress on a groundwater resource system can occur when withdrawals exceed natural recharge. Withdrawal of groundwater by wells is a stress superimposed on a previously balanced groundwater system. The response of an aquifer to pumping stress may result in an increase in recharge to the aquifer, a decrease in the natural discharge to streams, a loss of storage within the aquifer, or a combination of these effects, and impacts may extend beyond the limits of the aquifer being monitored.

Two major areas, primarily within the watersheds of the Upper Estuary and Schuylkill Valley, are showing signs of stress and are recognized as critical or protected areas: the Ground Water Protected Area in southeastern Pennsylvania and Critical Area #2 in south-central New Jersey which overlays the Potomac-Raritan-Magothy (PRM) aquifer (Fig 2.4.1). New and/or expanded withdrawals in both critical areas are limited and managed by specific regulations which serve to allocate the resource on the basis of a sustainable long-term yield.

2.4.2 Present Status

Conjunctive use strategies, or the practice of storing surface water in wet years for use during dry years, and regional alternatives to the local supplies are easing the stress in these two areas.

In the Southeastern Pennsylvania Ground Water Protected Area (SEPA-GWPA), reductions in total annual groundwater withdrawals have been observed over the past two decades (Fig 2.4.2). The DRBC and the Commonwealth of Pennsylvania created a management program for this area in 1980. In 1999 numerical withdrawal limits were established for each of the area's 76 sub-basins. This is the only area in the Basin for which the Delaware River Basin Commission has established cumulative water withdrawal limits. Between 1990 and 2013, total annual groundwater withdrawals within the SEPA-GWPA were reduced by approximately 8.5 billion gallons (23.4 mgd). A significant component of this reduction is the diversion of surface water from the Point Pleasant, PA intake on the Delaware River in the mid-1990s. The diversion alleviated the need for groundwater withdrawals for two major public water supply systems, as well as provided additional supply to Exelon's nuclear power station at Limerick, PA on the Schuylkill River. This diversion has provided a "conjunctive use" solution (i.e., adaptive use of both ground and surface water) that has reduced the reliance on groundwater in several sub-basins. Other sub-basins that were identified as stressed, or potentially stressed, have remained static, as sub-basin cumulative withdrawal limits have prevented further exacerbation of the stress.

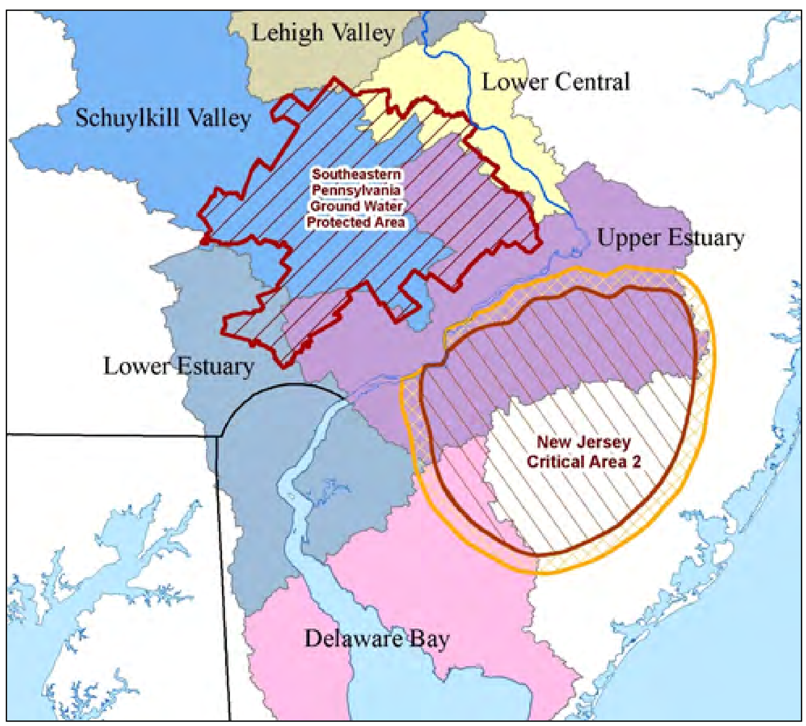

Figure 2.4.1 Areas of groundwater stress in the Delaware River Basin.

2.4.3 Past Trends

As shown in Figure 2.4.2, reduction in groundwater withdrawals in the SEPA-GWPA are largely due to the adoption of sub-basin withdrawal limits by DRBC in 1999. Groundwater pumping in several sub-basins has been reduced by the Point Pleasant diversion, which transfers surface water from the Delaware River to the GWPA. Other aspects of the management program administered by the DRBC in this area include a more aggressive water conservation program and a lower threshold of 10,000 gallons/month triggering regulatory review (as compared to 100,000 gallons/month elsewhere in the Delaware River Basin).

The New Jersey Water Supply Critical Area #2 was established by the State of New Jersey in 1996 and has resulted in reduced withdrawals from the Potomac-Raritan-Magothy (PRM) aquifer system. Many of the municipalities are now served by surface water diverted from the Delaware River near Delran, NJ. Because of conjunctive use of ground and surface water, aquifer levels have risen and appear to be stabilizing in most parts of Critical Area #2. An example is shown in the graph from USGS Elm Tree 3 Observation well (Fig 2.4.3), which is located more than 700 ft below land surface in the Middle PRM aquifer in Camden, NJ.

Further demonstrating the value of conjunctive use is Figure 2.4.4, which shows water withdrawals by the New Jersey American Water Company (Western Division) over the past two decades. The figure illustrates how the Delran surface water intake has simultaneously provided water to meet increasing demands and reduced the need for pumping from groundwater sources.

2.4.4 Future Predictions

Groundwater conditions in the SEPA-GWPA and NJ Critical Area #2 are expected to continue to improve over time due to management strategies of the DRBC, Pennsylvania, and New Jersey. Limits on groundwater withdrawals in conjunction with surface water diversion should allow continual recovery of those aquifers. An additional area of concern for groundwater resources is the PRM aquifer system, which extends from

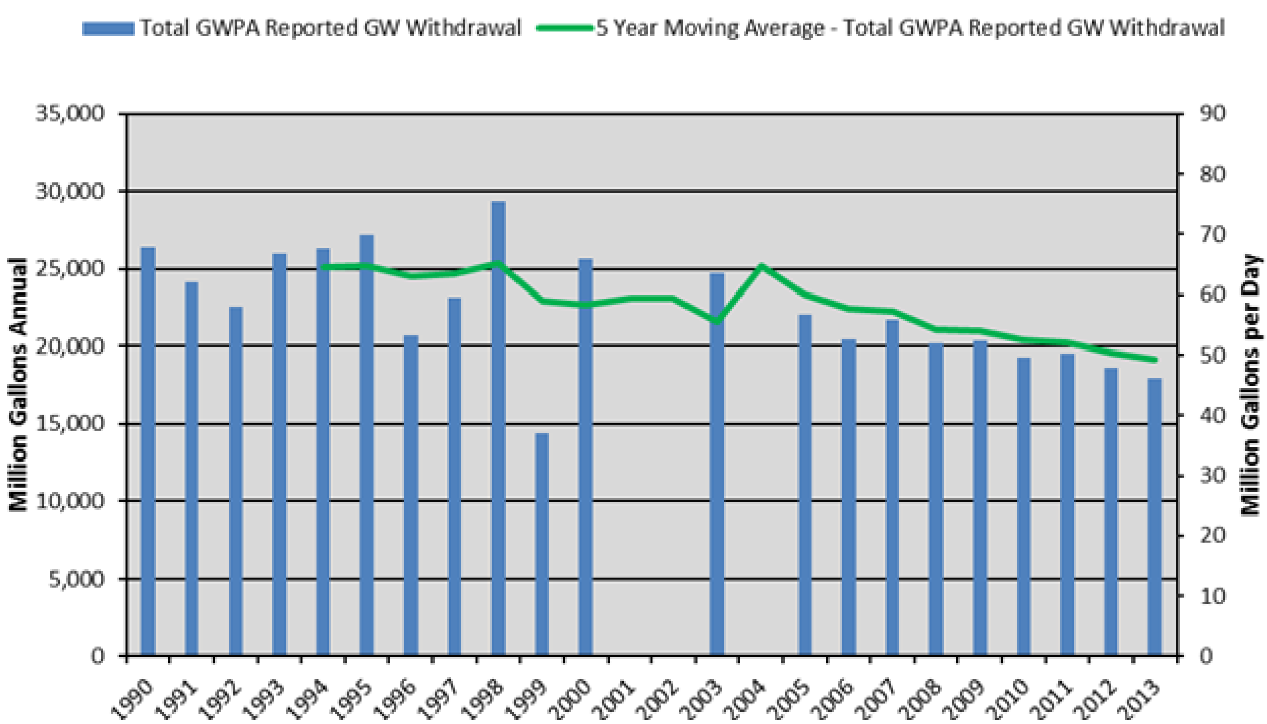

Figure 2.4.2 Groundwater withdrawals in the PA groundwater protected area 1990-2013.

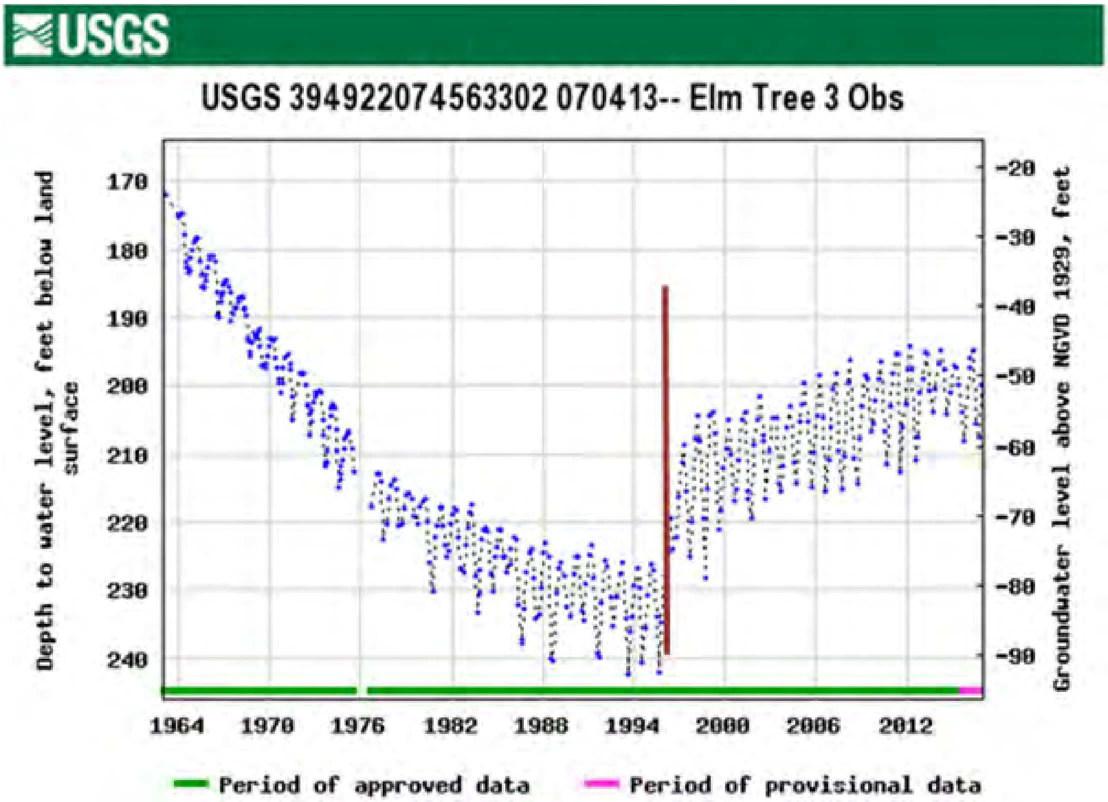

Figure 2.4.3 USGS Elm Tree 3 Observation Well.

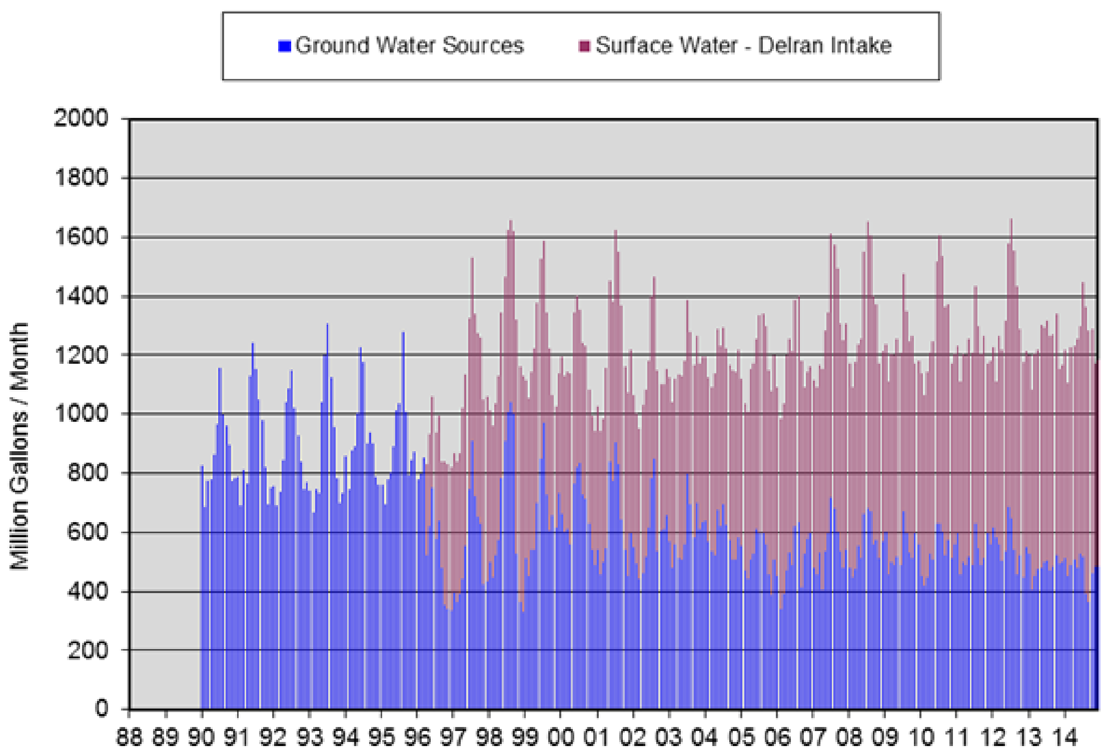

Figure 2.4.4 Water withdrawals by New Jersey American Water Company – Western Division.

New Jersey under the Delaware River, through the State of Delaware and into portions of Maryland. A 2007 report from the USACE on a groundwater model developed for northern New Castle County in Delaware concluded that groundwater withdrawals in Delaware have resulted in diminishing stream baseflows and cones of depression. The impact of these withdrawals extends into Maryland and New Jersey. In recent years, Delaware has developed a program to enhance water supplies from surface sources for northern New Castle County and is better positioned to withstand pressures of additional demand or a prolonged drought. Baseflow declines are still of concern in the Salem-Gloucester area and the Maurice River basin of southern New Jersey. New and/or expanded allocations are being denied or restricted to limit adverse impacts on the aquifers and to protect stream flows.

2.4.5 Actions and Needs

The progress made in recent years to improve water use reporting needs to be continued in order to provide the necessary data to monitor conditions in sensitive areas such as the southeastern Pennsylvania Ground Water Protected Area and the New Jersey Water Supply Critical Area #2. The metrics used to quantify groundwater availability in the GWPA could easily be applied to other areas of the Basin for assessment purposes. Attention should be paid to the PRM aquifer system, which extends through New Jersey, Delaware and into portions of Maryland, and is being impacted by groundwater withdrawals in Delaware.

2.4.6 Summary

The two groundwater areas described in this section are examples of successful, proactive management strategies that could be applied to other areas undergoing stress as a result of pumping groundwater. Further assessment of the PRM aquifer system is needed so plans to alleviate the impact of groundwater withdrawals in Delaware may be put in place.

2.5 Salt Front Location and Movement

2.5.1 Description of Indicator

The salt front is an estimation of where the seven-day average chloride concentration equals 250 ppm (parts per million) along the tidal Delaware River. The location of the salt front plays an important role in the Delaware River Basin water quality and drought management programs because upstream migration of brackish water from the Delaware Bay during low-flow and drought conditions could increase sodium concentrations in public water supplies, presenting a health concern. Critical intakes on the Delaware River that could be adversely affected by salinity moving upstream are the Philadelphia Water Department's Baxter intake and the New Jersey American Water Company's Delran intake. Both intakes are located at approximately river mile 110 (river kilometer 176). In addition, upstream migration of the salt front could adversely affect the PRM aquifer. High rates of pumping in the PRM draw tidal river water into the aquifer. If the salt front were to move too far upstream for an extended period of time, the presence of sodium could reduce the quality of water in the aquifer.

2.5.2 Present Status

The present day status of drinking water intakes are very good since the Tidal River is effectively protected by normal hydrologic conditions. Reservoir operations and water quality in the PRM remain very good.

2.5.3 Past Trends

The salt front naturally advances and retreats with each tidal cycle and with seasonal variations in freshwater flow. For most of the year, the location of the salt front is between the Commodore Barry Bridge (RM 82/KM 131) and Artificial Island (RM 54/KM 86). During droughts and periods of very low inflow to the Estuary, a management program releases water from upstream reservoirs to augment flows and to meet a daily flow target of 3,000 cubic feet per second (84.9 cubic meters per second) in the Delaware River at the Trenton, NJ gage. The program has worked well; since 1970, low-flow values that once occurred 10% of the time now occur only 1% of the time. The salt front has been successfully maintained below drinking water intakes, protecting drinking water supplies in the most urbanized area of the Basin (Fig 2.5.1).

Figure 2.5.1 shows the maximum upstream location, lowest measured downstream location and median location of the salt front for each year during the period 1989 to 2016 compared to locations of interest along the Delaware River. (Note that the salt front location is not tracked and recorded below river mile 54 (river kilometer 86), and that the 250 ppm isochlor may move further downstream than this location, but this is not shown in Fig 2.5.1). Figure 2.5.2 shows similar information in map form.

2.5.4 Future Predictions

Sea level rise and increasing variability in flow from climate change may create additional challenges for management of the salt front in the future.

2.5.5 Actions and Needs

An investigation of additional sources of chlorides, such as from road salts and runoff, is warranted. An evaluation of the adequacy of the 3,000 cfs target at Trenton, NJ in repelling the salt front is also warranted.

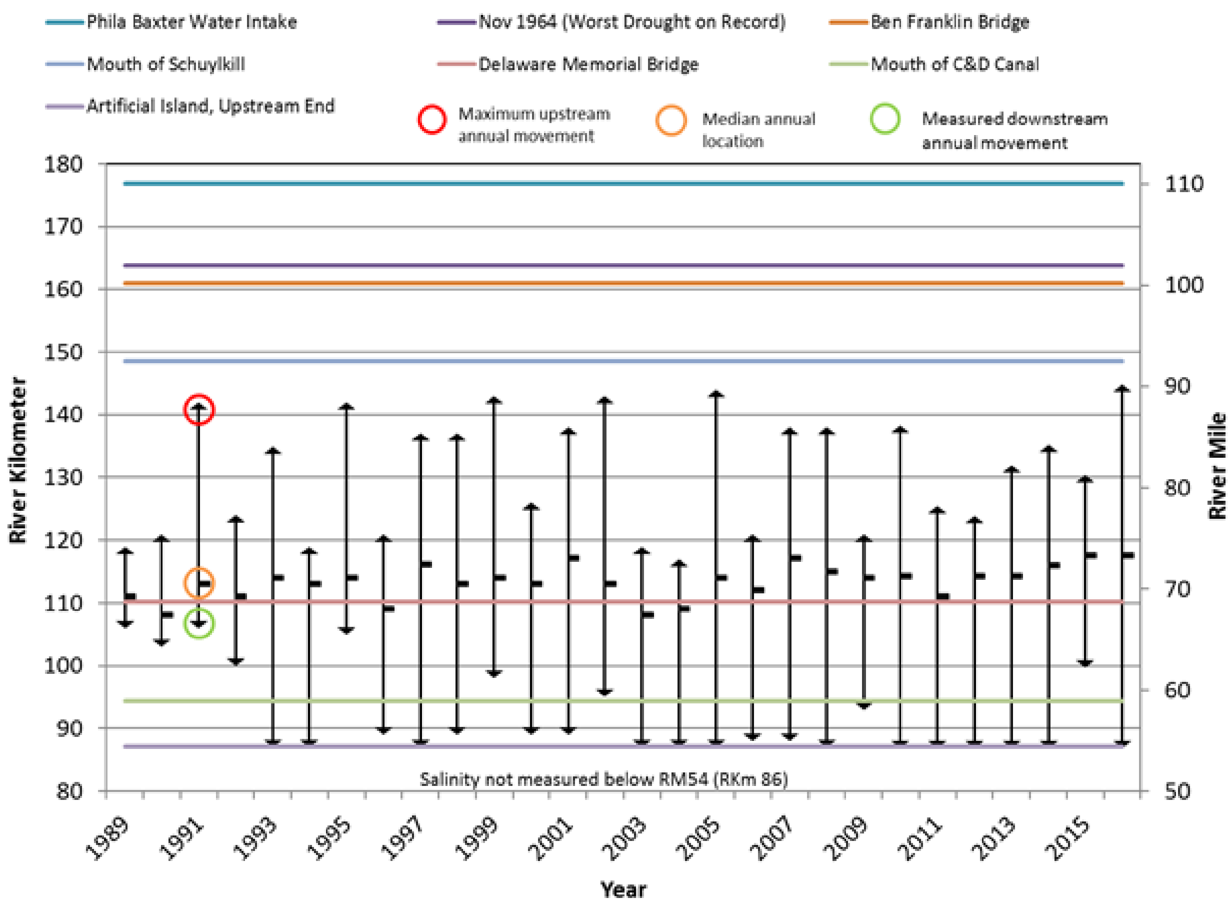

Figure 2.5.1 Range of annual salt front locations From 1989-2016. The salt front river mile location is estimated by DRBC using data provided by USGS and the Kimberly Clark Corporation.

2.5.6 Summary

Flow management strategies have been successful in restricting the upstream movement of the salt front and have effectively protected drinking water intakes in the most densely populated area of the Basin.

Data Sources

Several of the indicators described in this chapter are based on water withdrawal datasets (Table 2.5.1). These data are typically reported annually by water users to the state environmental agencies. To avoid duplication, data are provided by the state agencies to DRBC in order to complete Basin-wide assessments. In recent years several of the basin states have implemented web-based reporting processes which streamline data reporting and data management. As a result, the exchange of data has greatly improved, while further improvements are still necessary to achieve complete and timely data exchange. The merging, data checking, and compilation of water withdrawal data from the four Basin states requires significant staff and computational effort. For the purposes of this report, the calendar year 2014 was chosen as the target year for water withdrawals. In some cases, to fill data gaps or to obtain more recent data, the DRBC's own data sources have been used where available. These data come from DRBC's Surface Water Charging program which tracks surface water withdrawals from the Delaware River Basin.

Table 2.5.1 Summary of available water withdrawal data by state.

State	Year	Number of Withdrawals **	Volume of Withdrawals Million Gallons/Day (MGD)	Total Volume (%)
DE	2014	720	688	12
NJ	2014	3950	3611	63
NY*	2014	52	13	<1
PA	2014	2879	1390	24

* The New York City and New Jersey exportation of water from the Delaware River Basin and associated domestic use are not part of the data presented in the above table, but are included in the analysis in this chapter.

**The total number of withdrawals was calculated based on the total number of withdrawal points that reported data at some point during the period from 2010 through 2014.

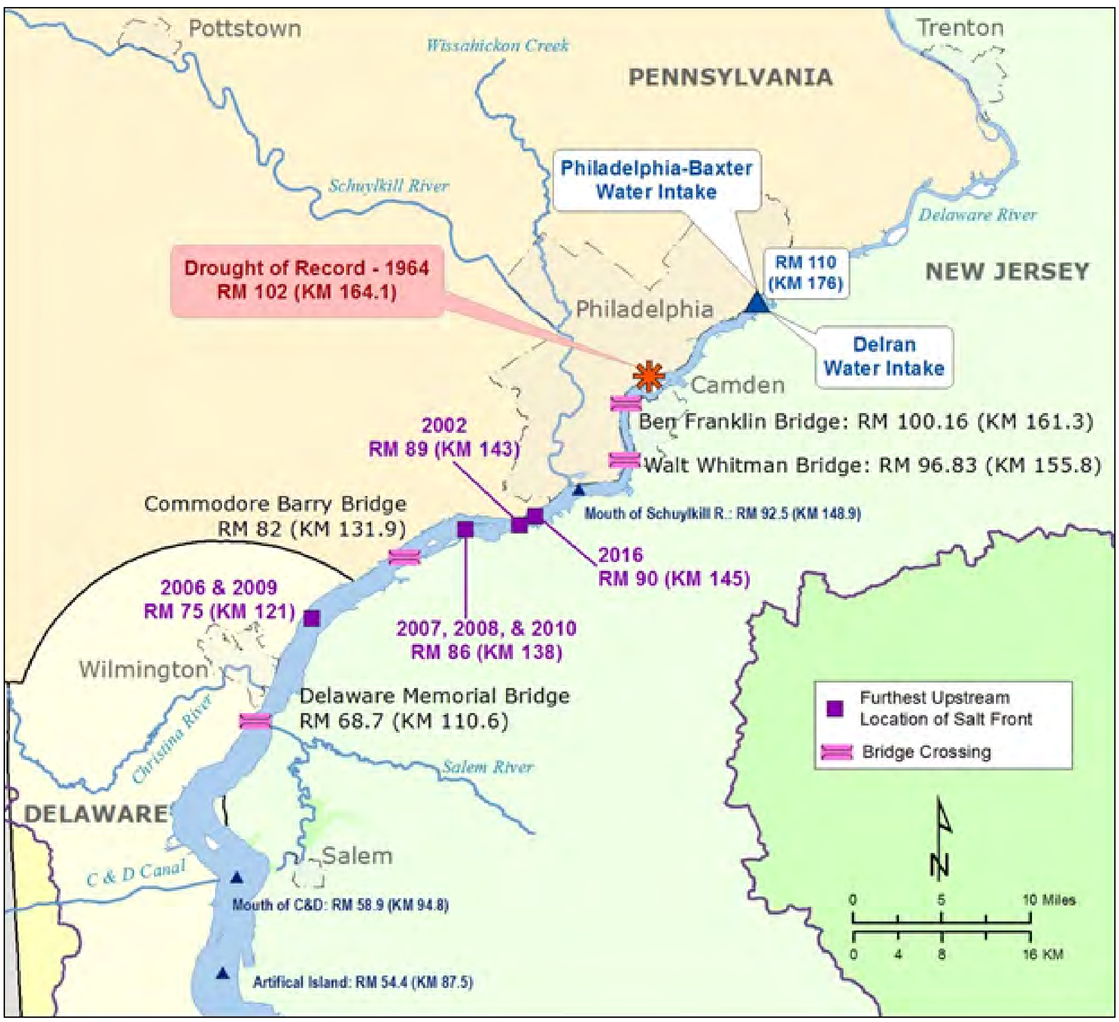

Figure 2.5.2 Map of historic salt front locations.

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Further Reading

New Jersey Water Supply Plan 2017-2022 http://www.nj.gov/dep/watersupply/pdf/wsp.pdf

Suggested Citation for this Chapter

Barr, J. K. 2017. 2017. "Chapter 2 - Water Quantity" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 77-95.

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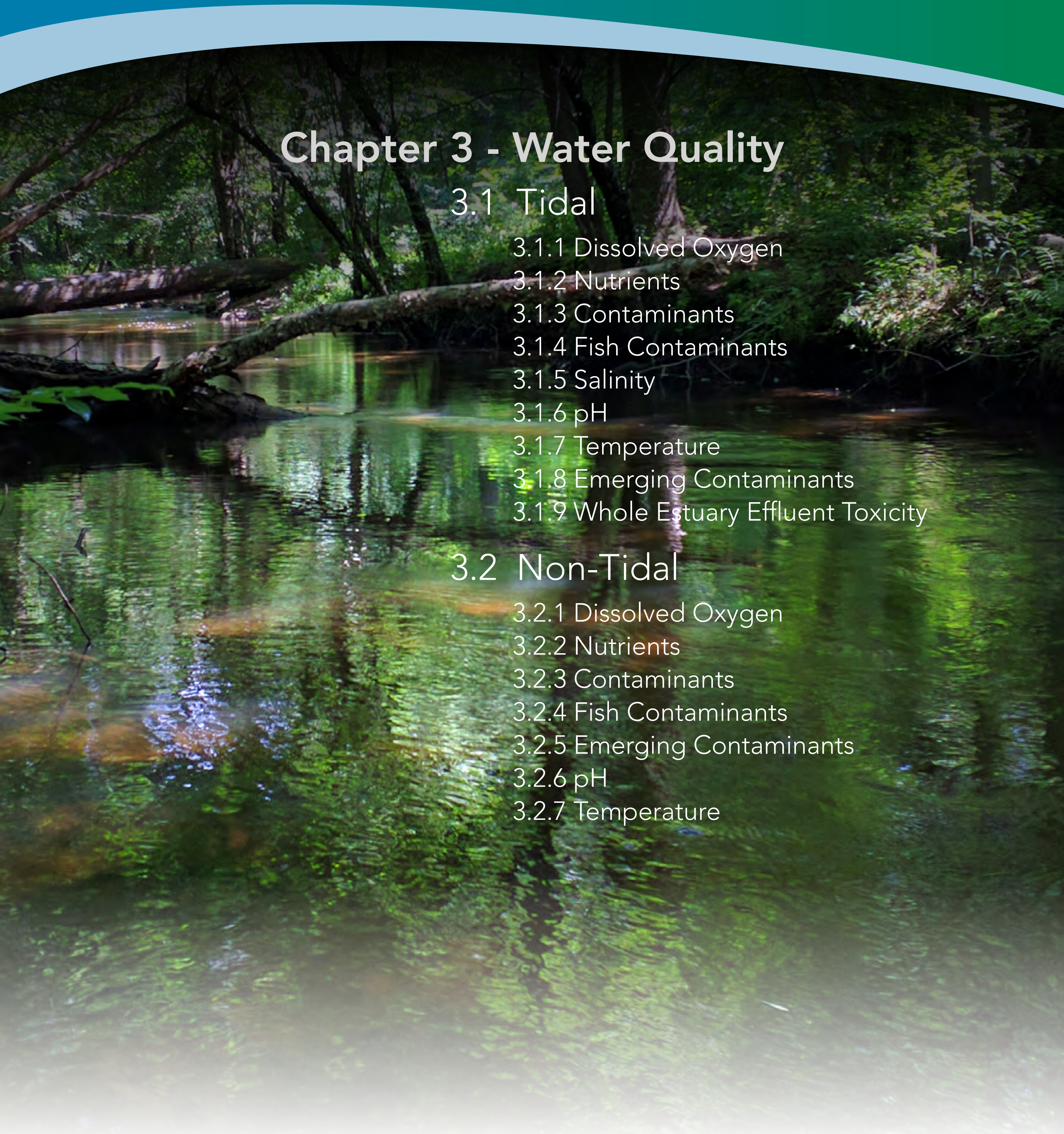

Chapter 3 - Water Quality

Partnership for the DELAWARE ESTUARY

December, 2017 | Report No.17-07

A publication of the Partnership for the Delaware Estuary—A National Estuary Program

3. Water Quality

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Delaware River Basin Commission

3.1 Tidal

3.1.1 Dissolved Oxygen

3.1.1.1 Description of Indicator

Dissolved oxygen (DO) refers to the concentration of oxygen gas incorporated in water. Oxygen enters water both by direct absorption from the atmosphere, which is enhanced by turbulence, and as a by-product of photosynthesis from algae and aquatic plants. Sufficient DO is essential to growth and reproduction of aerobic aquatic life. Oxygen levels in water bodies can be depressed by the discharge of oxygen-depleting materials (measured in aggregate as biochemical oxygen demand, BOD, from wastewater treatment facilities and stormwater runoff), from the decomposition of organic matter including algae generated during nutrient-induced blooms, and from the oxidation of ammonia and other nitrogen-based compounds. The Delaware Estuary has historically been plagued by anoxic and hypoxic conditions (the lack of oxygen or the severe depression of oxygen, respectively) that resulted from the discharge of raw and poorly treated wastewater. Although the Estuary has seen a remarkable recovery since the 1960s, with fish such as striped bass and sturgeon now able to spawn (at least some of the time) within the Estuary, dissolved oxygen remains a critical issue for the Estuary because of continued depression of oxygen levels below saturation.

3.1.1.2 Present Status

Dissolved oxygen is measured routinely as part of the Delaware River Basin Commission's (DRBC) Delaware Estuary Water Quality Monitoring Program (formerly the Boat Run) and continuously by the U.S. Geological Survey (USGS) at Reedy Island (01482800), and April through November at Chester (01477050), and the Ben Franklin Bridge (01467200). DRBC's water quality standard for dissolved oxygen in the Estuary is a 24-hour average concentration not less than 5.0 mg/L in Zone 2, 3.5 mg/L in Zones 3, 4, and the upper portion of Zone 5, 4.5 mg/L in the middle portion of Zone 5, and 6 mg/L in the lower portion of Zone 5. In the most recent Delaware River and Bay Water Quality Assessment (DRBC 2016 http://www.state.nj.us/drbc/library/documents/WQAssessmentReport2016.pdf), greater than 98.5% of observations met criteria in Zones 2 through 5, and greater than 90% of observations met criteria in Zone 6.

DRBC has developed a daily near real-time assessment of DO comparing the 24-hour mean concentrations at USGS monitors to the DRBC surface water quality standard available at:

http://drbc.net/Sky/waterq.htm

In addition, DRBC has developed a web app for exploring the Estuary Water Quality Monitoring data at:

https://johnyagecic.shinyapps.io/BoatRunExplorer/

Figure 3.1.1 shows a screen shot of the DRBC Delaware Estuary Water Quality Explorer web application, which allows users to develop their own visualizations of Delaware Estuary water quality data. This selection shows the structure of dissolved oxygen along the profile of the Estuary as measured by the Delaware Estuary Water Quality Monitoring program. As shown, dissolved oxygen saturation levels are higher at the upper and lower ends of the Estuary, with a sag in the most urbanized portion of the Estuary.

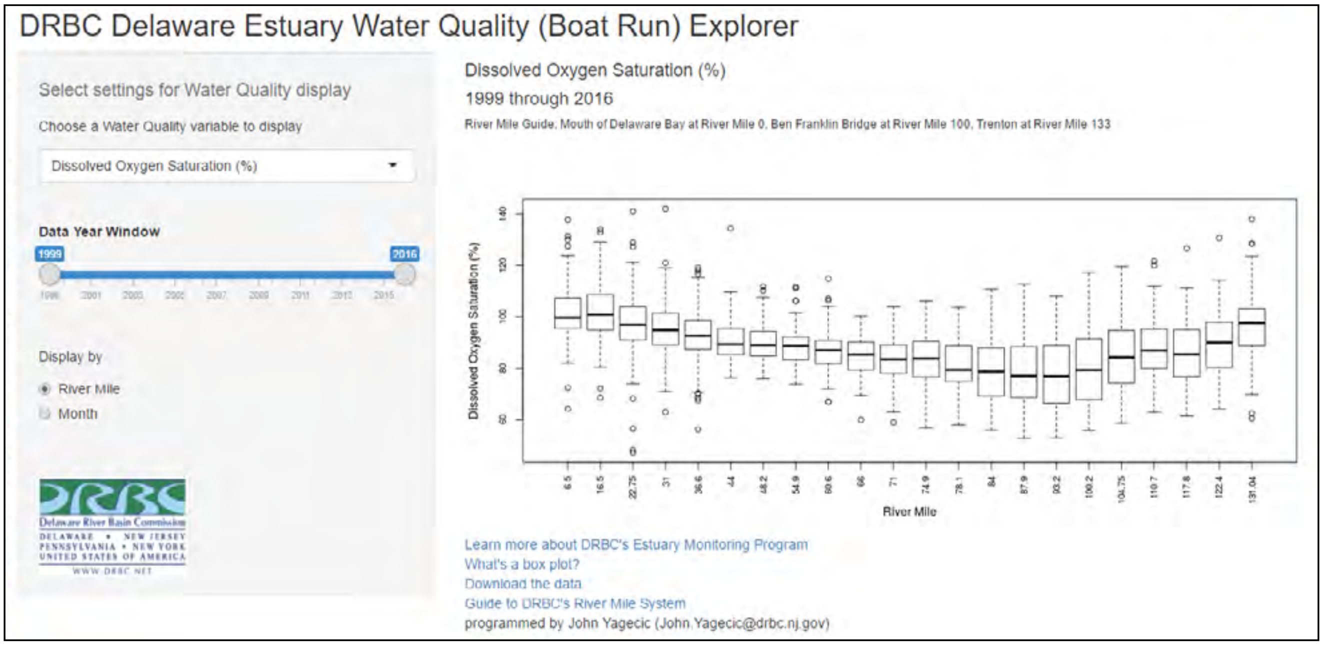

Figure 3.1.1 Delaware Estuary dissolved oxygen saturation measured as part of the DRBC Delaware Estuary Water Quality Monitoring Program, 1999 through 2015.

The USGS continuous monitor data (Fig 3.1.2) shows that dissolved oxygen concentrations are highest at Reedy Island (River Mile 54.1), lower at Chester (River Mile 83.1) and lowest at the Ben Franklin Bridge (River Mile 100.05).

3.1.1.3 Past Trends

USGS' continuous dissolved oxygen measurements began in 1964. Historically, DO concentrations are lowest in mid-summer. As shown in Figure 3.1.3, the July dissolved oxygen concentrations were historically below the current Zone 3 standard of 3.5 mg/L in the 1960s and 1970s. Improvements in DO became apparent through the 1980s as municipal waste water treatment facilities added secondary treatment for sewage. From the mid 1990s onward, criteria were mostly met, although DO concentrations exhibit a high level of variability from year to year. DO at the Ben Franklin Bridge for example was mostly above 6 mg/L in 2014 and 2015, but closer to 5 mg/L in 2016. Figure 3.1.4 shows box plots for daily minimum DO at the same location, over the same time period.

Figure 3.1.5 is a box and whisker plot of all July daily mean % of dissolved saturation values by year for the Delaware River at the Ben Franklin Bridge. Since % of saturation was not historically reported at this location, values were computed using the daily mean water temperature and atmospheric pressure, and assuming specific conductance of 229 uS/cm (the median for this location for this period of record) using the USGS DO Tables application. Although DO measurements are available starting in 1965, atmospheric pressure measured at the Philadelphia International Airport is available starting in 1973 only.

To gain deeper insight into the trends of DO at the USGS monitors in the Estuary, DRBC time series decomposition algorithms were applied to the daily mean DO time series. For winter medians when monitoring is discontinued, 100% saturation values were assumed for missing data. For other missing data, the monthly mean DO was substituted for that location. The time series decomposition tool breaks the overall time series into a repeating seasonal pattern, trend, and remainder (i.e. error not explained by seasonal pattern and trend). By removing the seasonal pattern, time series decomposition helps make clear

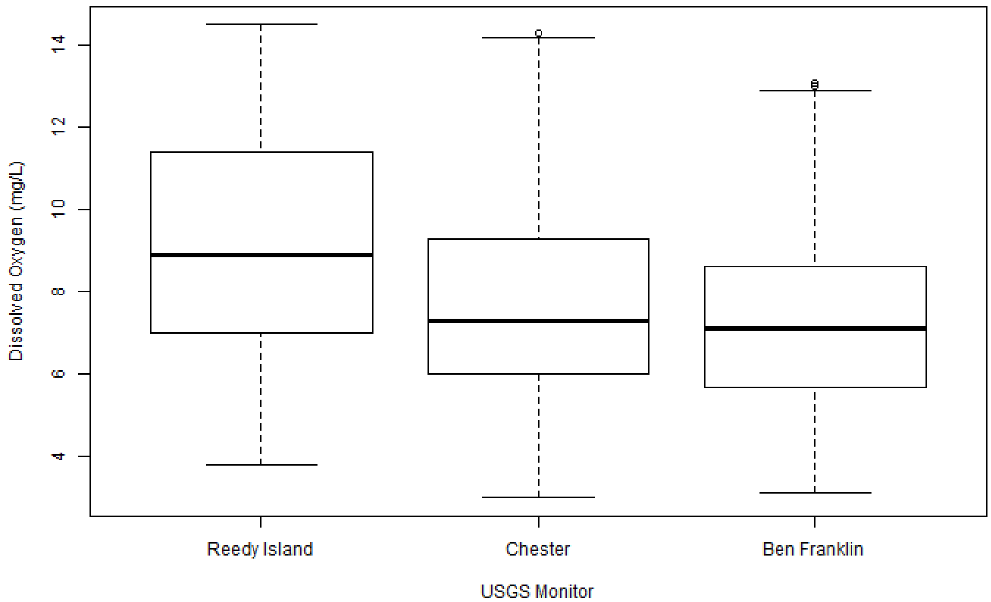

Figure 3.1.2 Delaware Estuary Dissolved oxygen measured by USGS continuous monitors, 2011 through 2016.

the long term trend. Time series decomposition was used to examine DO data from 2000 through 2015 for the USGS monitors at Ben Franklin Bridge, Chester, and Reedy Island (Figs 3.1.6, 3.1.7, and 3.1.8). Ben Franklin seems to show no apparent trend from the mid 2000s through 2015 but with high variability and an apparent dip at the end of the time series reflecting 2016. Chester appears to be characterized by high variability , but with lowest DO levels occurring prior to 2006. Reedy Island appears to show a continuing trend of improved DO concentrations from the early 2000s through 2015.

For each of the time series decomposition plots, the y-axis in the top "data" panel shows the base units, in this case fraction of saturation. The y-axis units for the "seasonal" and "remainder" panels are the same relative units, but centered at 0, thus describing the relative range of these influences. The y-axis units for the "trend" panel are the same units, but limited to the range determined for that component. The gray bar on the right-hand side is a visual reference for the degree of exaggeration of the y-axis, relative to the "data" panel. A gray bar that is much longer than the gray bar in the "data" panel means that the variation attributable to that component has been exaggerated to aid in visual inspection.

3.1.1.4 Future Predictions

Documentation of fish spawning in the Delaware Estuary (Silldorff 2015) and a proposal to designate the Delaware Estuary as Critical Habitat for Atlantic Sturgeon (Endangered and Threatened Species; Designation of Critical Habitat for the Gulf of Maine, New York Bight, and Chesapeake Bay Distinct Population Segments of Atlantic Sturgeon, 2016) have highlighted a gap between the protectiveness of the current dissolved oxygen standard (24-hour mean concentration not less than 3.5 mg/L) in Zones 3, 4, and the upper portion of Zone 5 and the current ecological function of the Estuary. Achievement of higher DO concentrations will likely require tighter controls of the discharge of nutrients, especially ammonia. DRBC is currently in the process of developing a eutrophication model for the Delaware Estuary that will allow us to determine nutrient allocations needed to achieve higher dissolved oxygen concentrations.

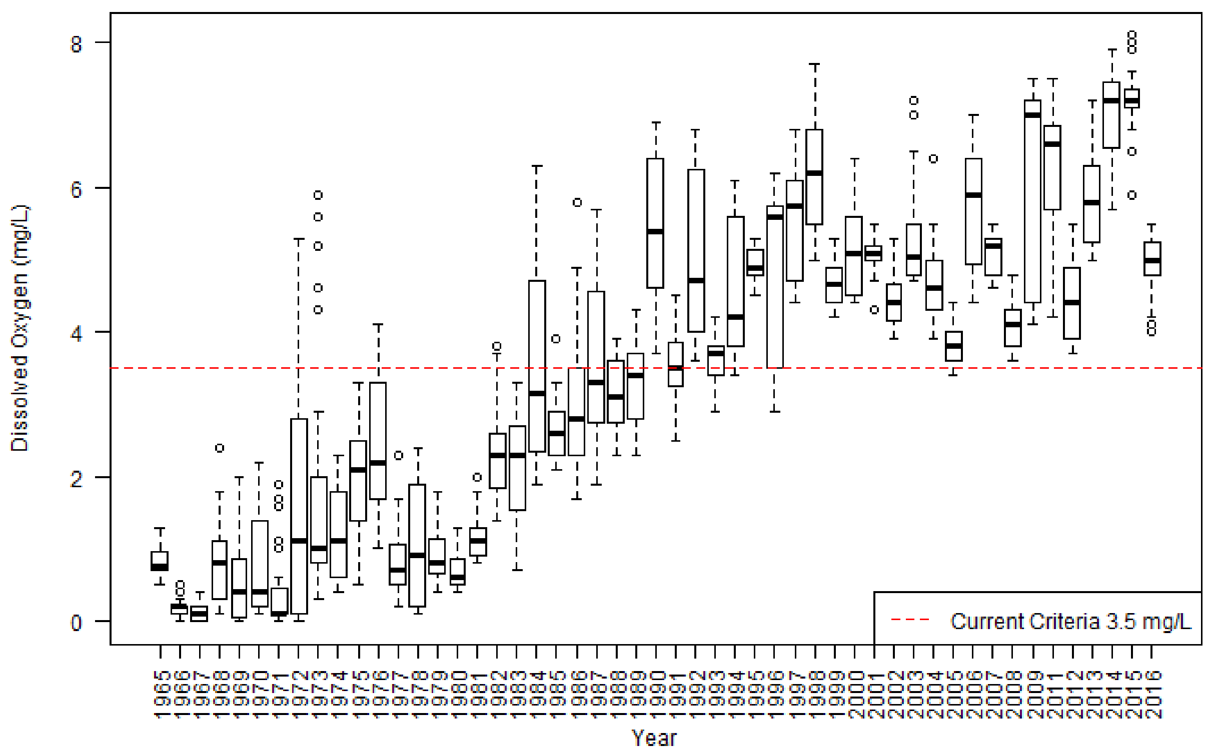

Figure 3.1.3 Delaware Estuary July daily mean dissolved oxygen concentrations by year at USGS at Ben Franklin Bridge, 1965 through 2016.

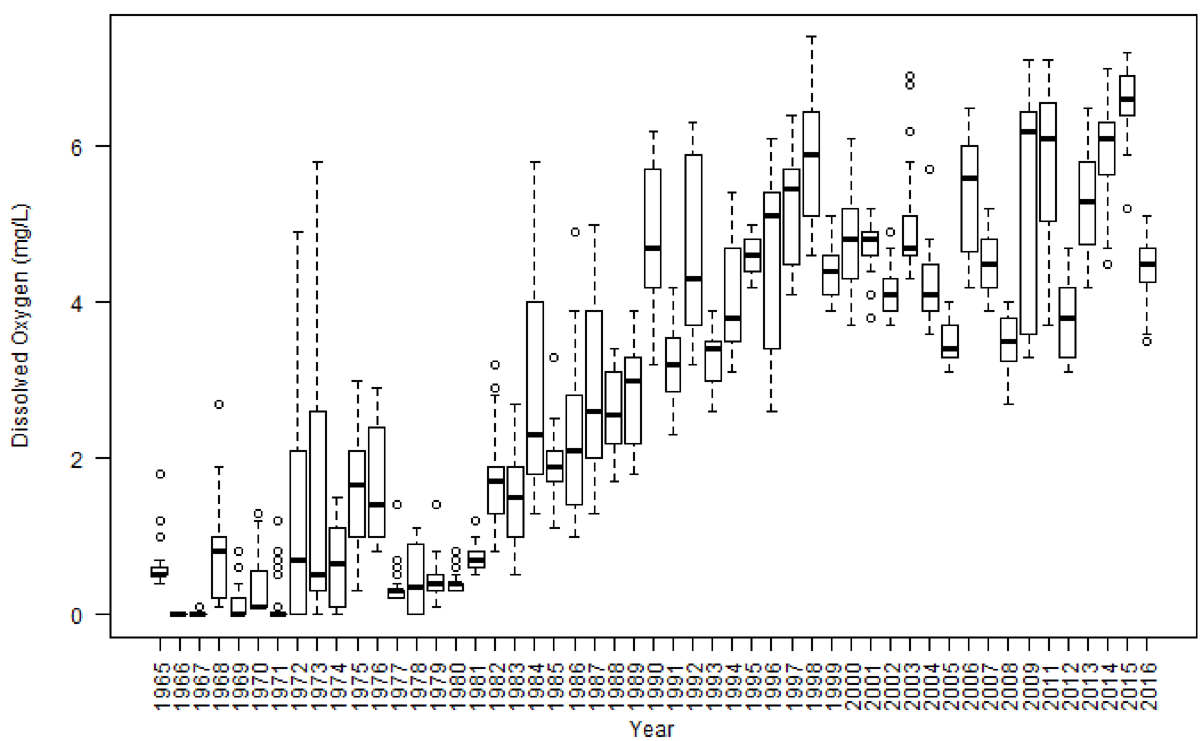

Figure 3.1.4 Delaware Estuary July daily minimum dissolved oxygen concentrations by year at USGS at Ben Franklin Bridge, 1965 through 2016.

3.1.1.5 Actions and Needs

DRBC has identified 2018 and 2019 as monitoring-intensive years in support of the estuary eutrophication model development. During that time period, we are requesting cooperating organizations to temporarily align monitoring initiatives and resources to focus on the Delaware Estuary in support of model development.

3.1.1.6 Summary

The long term trend of DO in the Delaware Estuary shows remarkable improvement from near anoxic conditions in the 1960s and 1970s to nearly always above criteria today. In order to capture and retain the recoveries in fish spawning that have followed the recovery in DO, DRBC is seeking to determine the appropriate designated aquatic life uses of the Delaware River Estuary and the water quality criteria necessary to protect these uses.

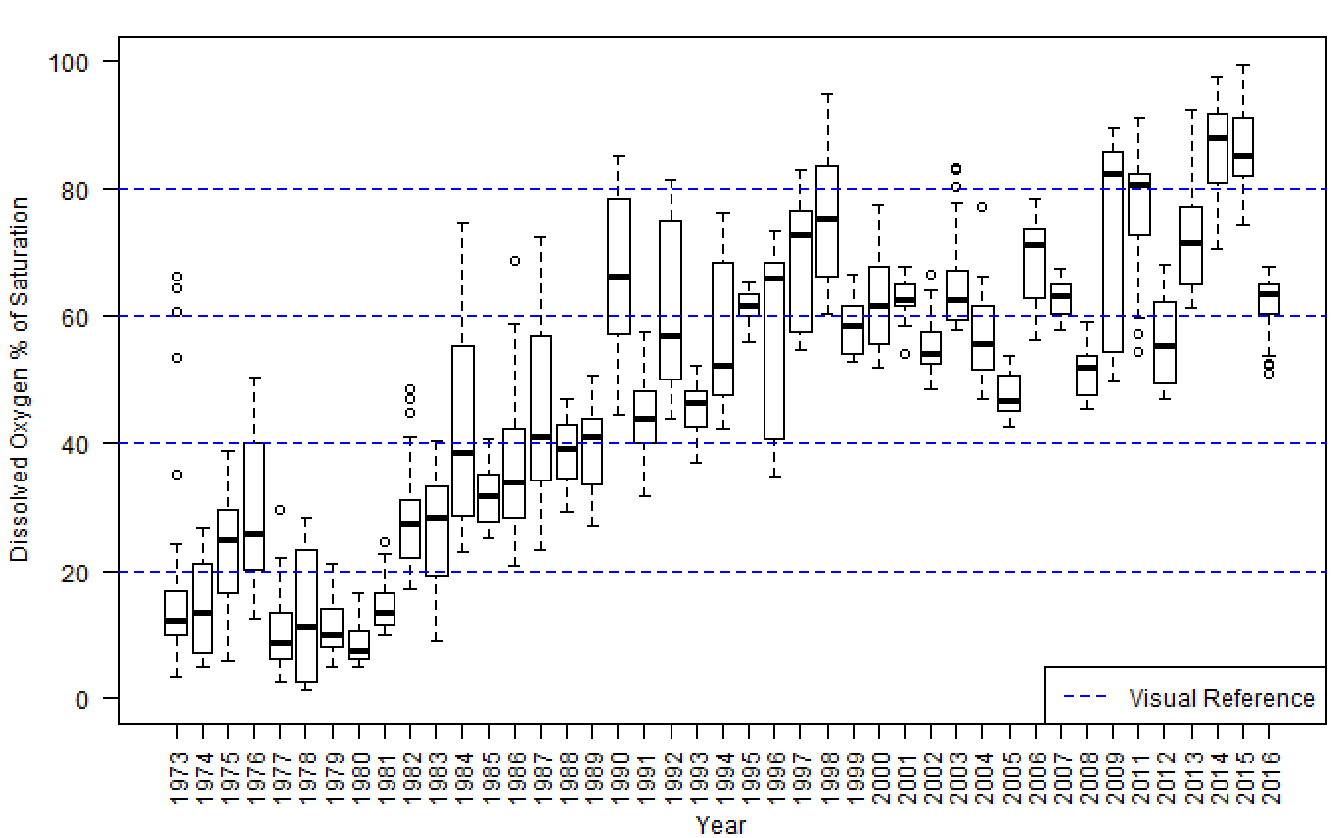

Figure 3.1.5 Delaware Estuary July mean daily dissolved oxygen percent of saturation by year at USGS at Ben Franklin Bridge, 1973 through 2016.

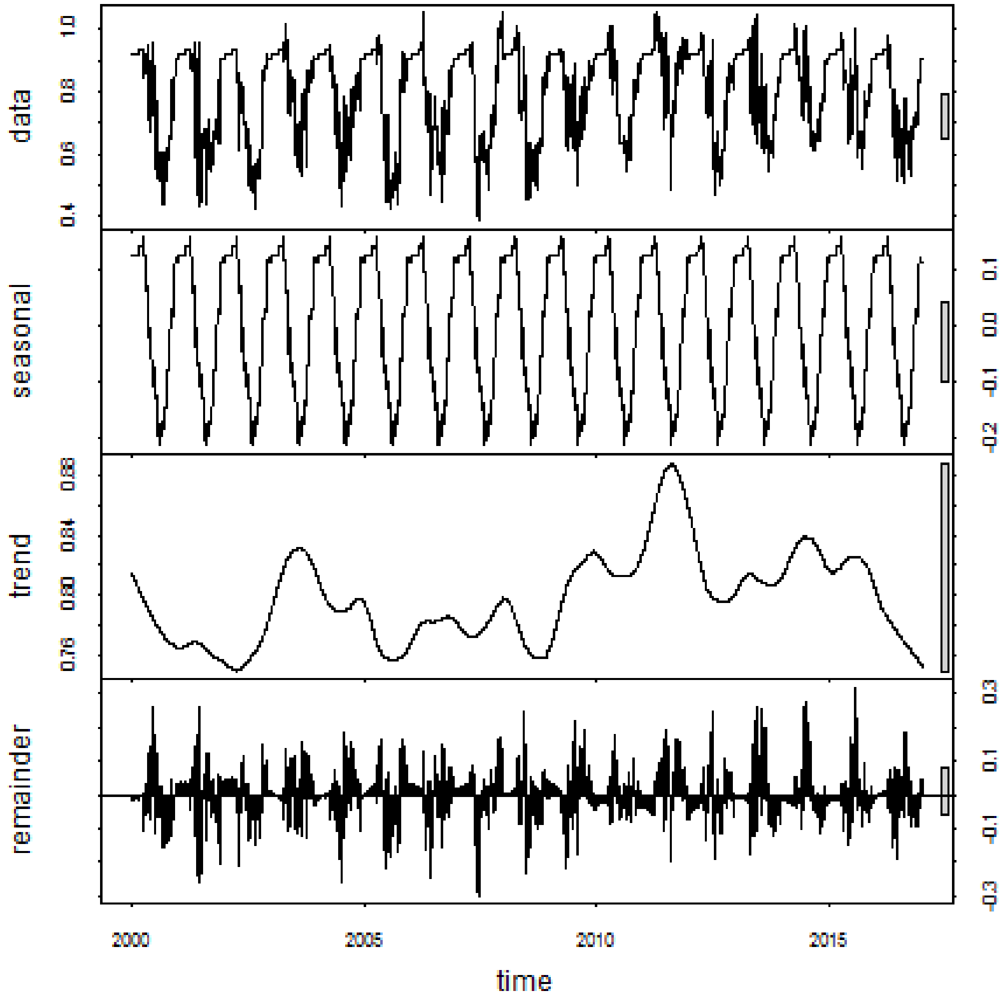

Figure 3.1.6 Time series decomposition, daily percent of dissolved oxygen saturation at USGS 01467200, Ben Franklin Bridge.

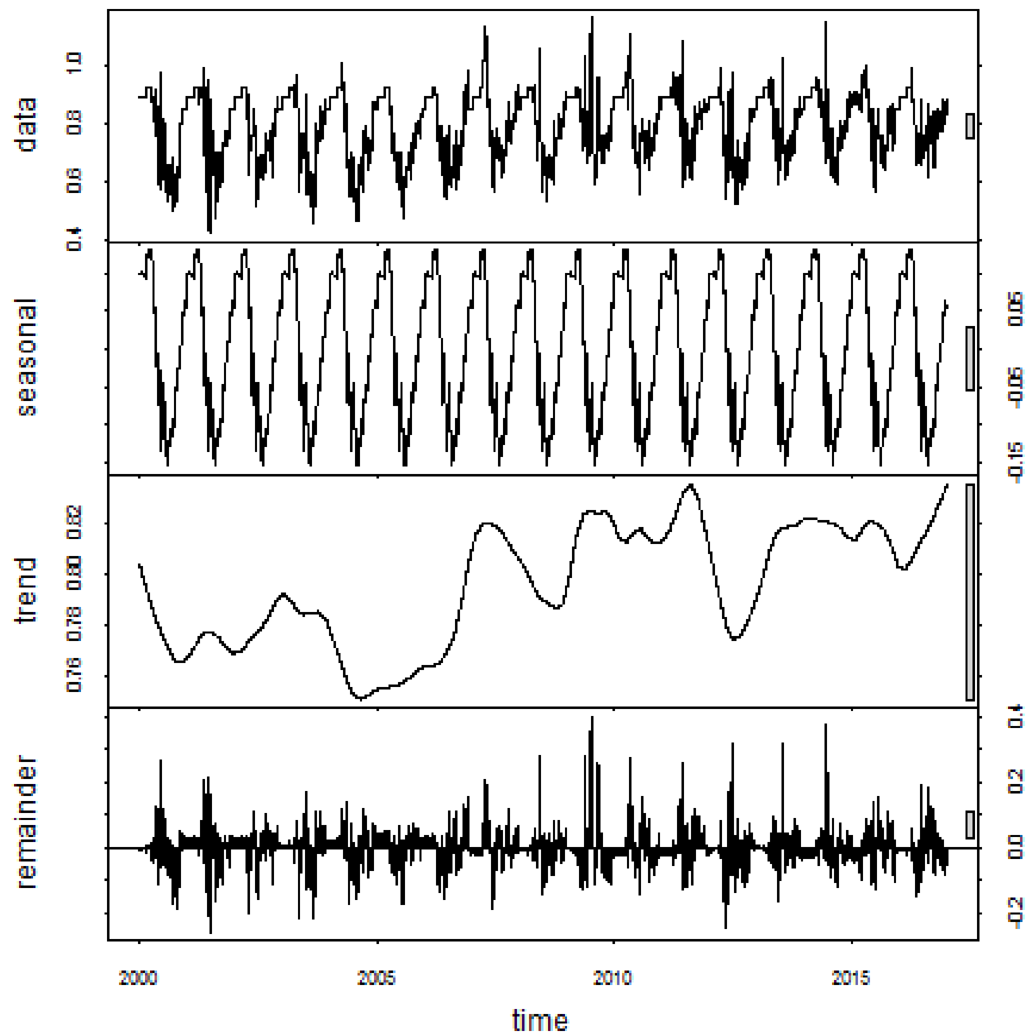

Figure 3.1.7 Time series decomposition, daily percent of dissolved oxygen saturation at USGS 01477050, Chester.

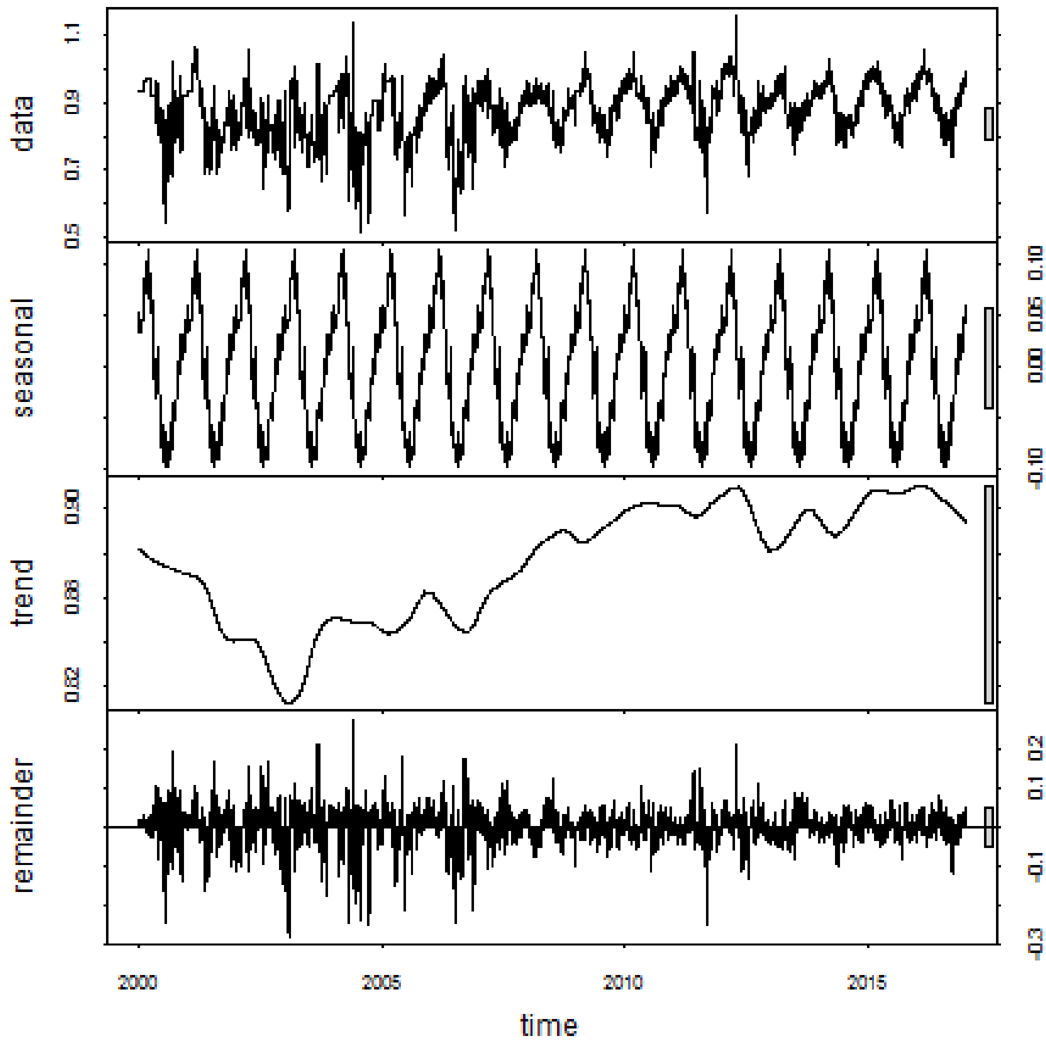

Figure 3.1.8 Time series decomposition, daily percent of dissolved oxygen saturation at USGS 01482800, Reedy Island.

3.1.2 Nutrients

3.1.2.1 Description of Indicator

The general category of "nutrients" is comprised of many different chemical compounds, including several species of nitrogen and phosphorus containing compounds. For this indicator, we considered specific chemical substances including nitrate, ammonia, and phosphate as being representative of nutrients. Nitrate and phosphate both have the advantage of being relatively quantifiable in the Estuary and having a long measurement record.

The Delaware Estuary has both high loadings and high concentrations of nutrients relative to other estuaries in the United States (National Estuary Program Coastal Condition Report, 2006). The effects from these high nutrients are not well-understood, but monitoring in the Estuary shows signs of suboptimal ecological health, including a persistent summer dissolved oxygen sag in the urban corridor of the Estuary. Although nutrient loading to the Estuary has not been demonstrated to be the cause of either suboptimal ecological conditions or the dissolved oxygen sag, high nutrient loading is one of the main candidates for understanding the Estuary's ecological health. Although nutrients are high, the worst eutrophication symptoms (such as anoxia, fish kills, and harmful algal blooms) are not currently seen in the Delaware Estuary.

3.1.2.2 Present Status

Phosphate measured as part of the DRBC Delaware Estuary Water Quality Monitoring Program shows highest concentrations near the most urbanized portion of the Estuary with lower concentrations near the head of tide and the mouth of the Bay as shown in Figure 3.1.9.

Ammonia and nitrate concentrations in the Estuary currently are typically less than 1 mg/L for ammonia and typically less than 3 mg/L for nitrate. Highest concentrations are observed in the urbanized mid area of the Estuary, with somewhat lower concentrations near the head of tide (reflecting lower concentrations in the non-tidal river) and substantially lower concentrations at the mouth of the Bay, as shown in Figures 3.1.10 and 3.1.11 below. This pattern suggests loadings originating in the Estuary, especially in the urbanized area. As stated previously, although nutrient concentrations in the Delaware Estuary are high, hypoxia and harmful algal blooms are not observed.

Monitoring for ammonia has been performed by the University of Delaware, and since 2009 by the Boat Run monitoring program, with funding from the USGS.

Nitrate concentrations in particular, as in Figure 3.1.11 below, show structure suggesting higher loads in the urbanized portion of the Estuary with dilution and possible uptake in the Bay.

3.1.2.3 Past Trends

To assess long term trends, data from the DRBC Delaware Estuary Water Quality Monitoring Program (formerly the Boat Run) were queried, from the late 1960s through 2016.

Nitrate is quantifiable throughout the data record and is expected to be the most prevalent form of nitrogen in the Delaware Estuary, thus providing a good approximation of nitrogen trends over time. Since nitrate in the Estuary has a defined spatial structure (Fig 3.1.11), we selected measurements between river kilometer 104.6 (River Mile 65) and 152.9 (95) as representative of the highest, uniform concentrations in the Estuary. Figure 3.1.12 below, depicting data points and smoothed curve, demonstrate relatively consistent concentrations since the early 1990s, with variable and sometimes higher concentrations in the 1970s.

Since phosphate data are sparse and shows less spatial structure, we selected all Estuary phosphate measurements to generate the long term trend shown in Figure 3.1.13 below. This graph shows much higher concentrations in the 1970s settling toward consistently lower concentrations typically less than 0.25 mg/L in the 2000s, but with a considerable data gap.

Comparison shows that both graphs are in general agreement with and continuation of the trends documented by Sharp et al. 1994.

3.1.2.4 Future Predictions

As mentioned previously, documentation of fish propagation in the Estuary and proposal to designate the Estuary as essential fish habitat for Atlantic Sturgeon compel the identification and adoption or more protective dissolved oxygen criteria. Conceptually, achievement of more protective dissolved oxygen standards will likely need to be achieved through tighter effluent limits on nutrients, especially ammonia.

DRBC is in the process of developing a eutrophication model for the Delaware Estuary. This model will allow DRBC to determine what level of dissolved oxygen is achievable and what limitations on nutrient discharges will be needed to achieve these limits.

3.1.2.5 Actions and Needs

DRBC and its partner organizations need to complete the estuary eutrophication model. The modeling

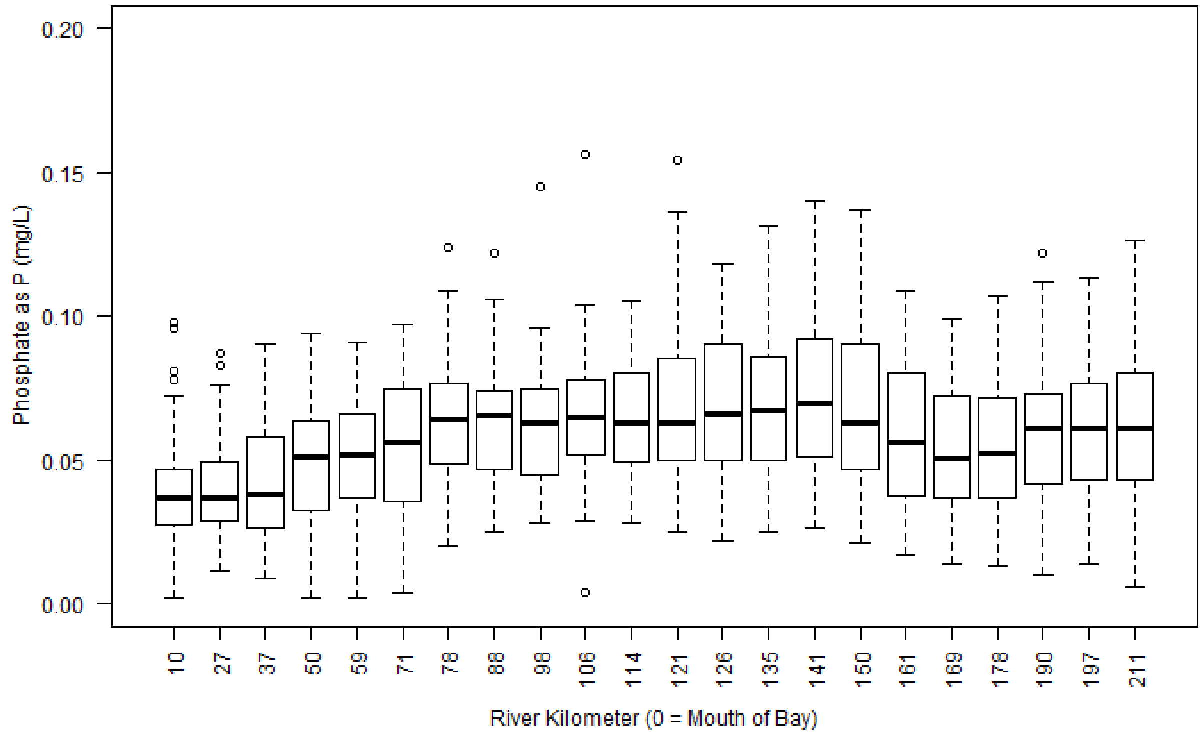

Figure 3.1.9 Phosphate by river kilometer in the Delaware Estuary, 2008 through 2016.

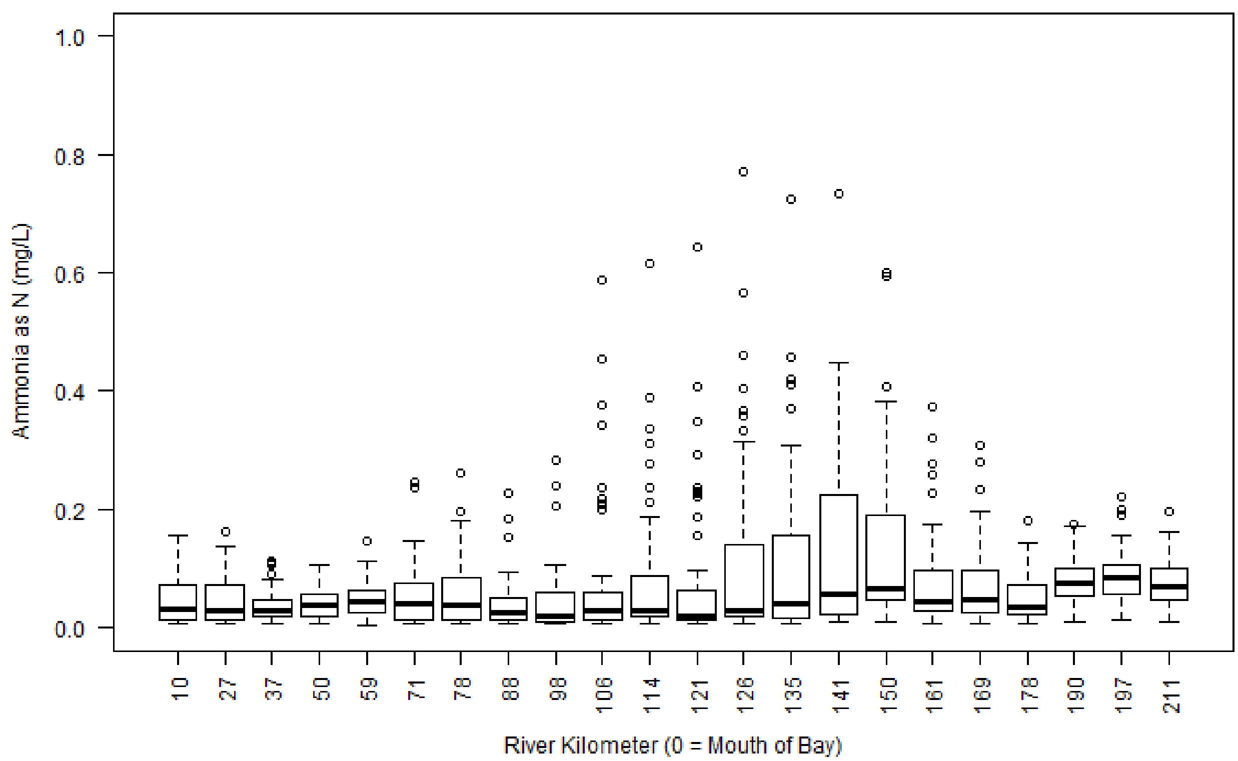

Figure 3.1.10 Ammonia by river kilometer in the Delaware Estuary, 2009 through 2010.

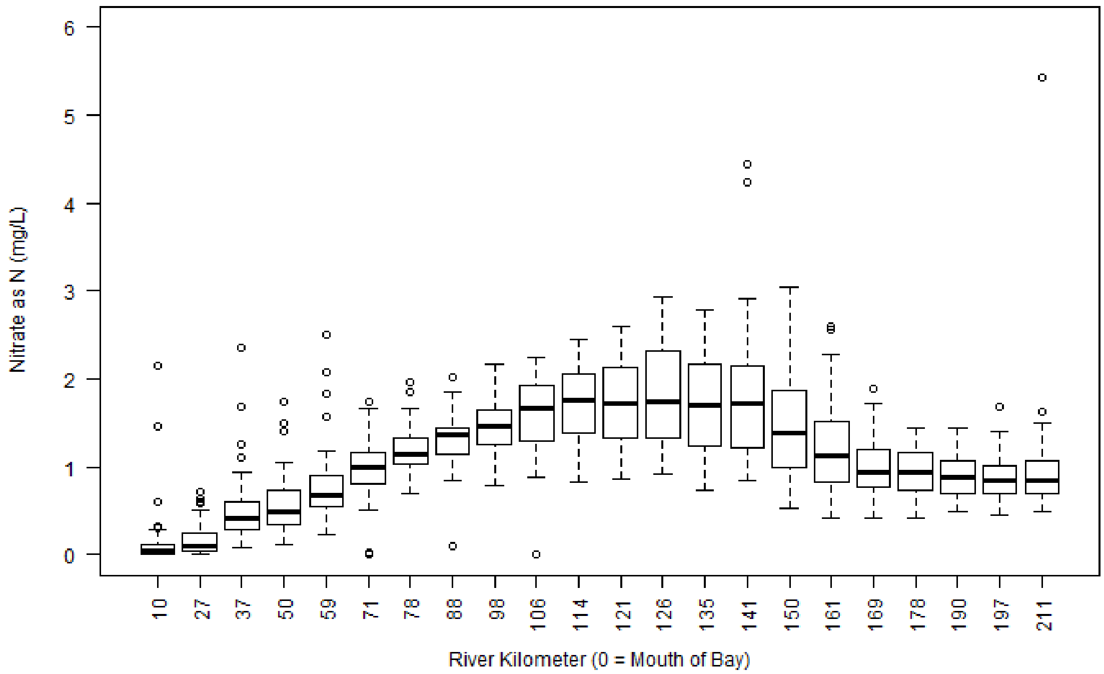

Figure 3.1.11 Nitrate by river kilometer in the Delaware Estuary, 2008 through 2016.

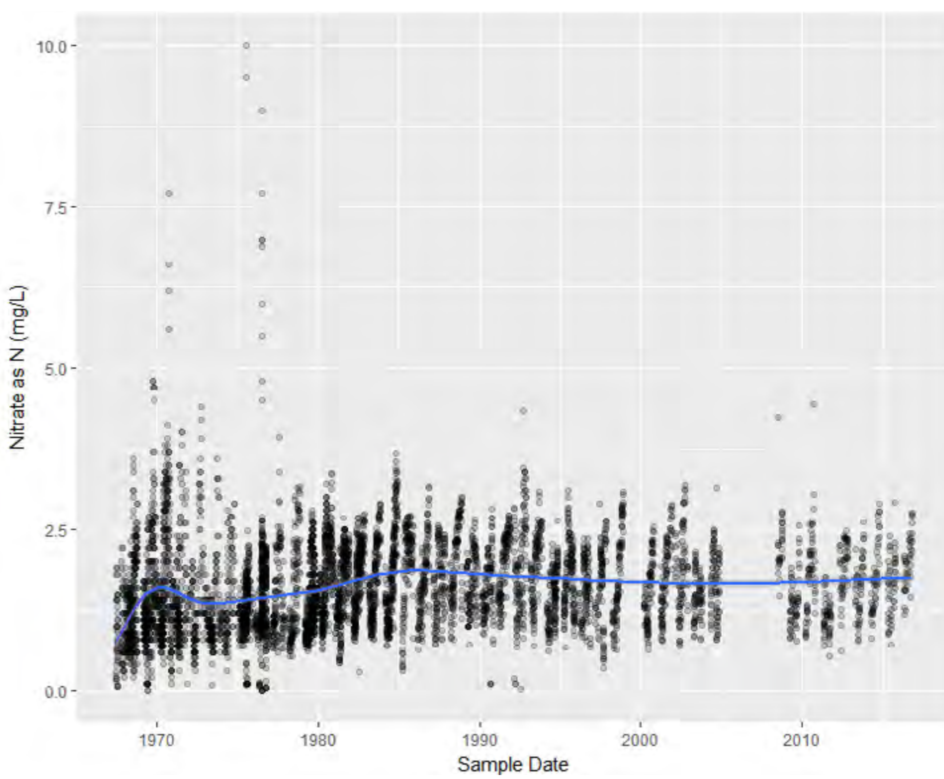

Figure 3.1.12 Historic nitrate in the Delaware Estuary from 1967 to 2016.

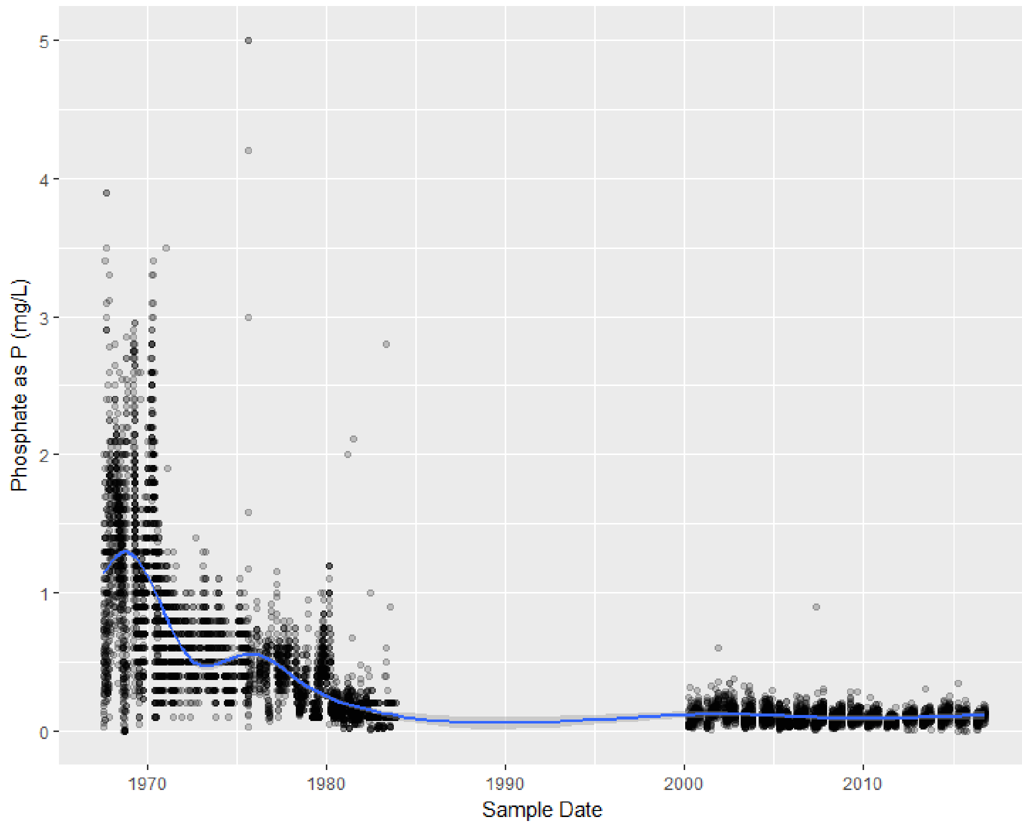

Figure 3.1.13 Historic phosphate in the Delaware Estuary from 1967 to 2016.

effort requires the assistance of partner organizations especially via enhanced data collection during the monitoring intensive period.

3.1.2.6 Summary

Delaware Estuary nutrient concentrations are lower than historical levels, but still elevated relative to other estuaries. DRBC is currently in the process of developing a eutrophication model for the Delaware Estuary that will allow us to determine nutrient allocations needed to achieve higher dissolved oxygen concentrations.

3.1.3 Contaminants

The "Contaminants" indicator is a general category for specific elements and compounds with varying degrees of toxicity to aquatic life and human health.

3.1.3.1 Description of Indicator

Water quality monitoring data from multiple organizations (DRBC, DNREC, NYSDEC, NJDEP, PADEP and USGS) are compared to stream quality objectives and narrative standard to evaluate water quality. The Delaware River Basin Commission (DRBC) has stream quality objectives for human health and aquatic life used in assessment of the tidal portion of Delaware River Basin from the head of tide at Trenton, NJ to the mouth of the Delaware Bay (Zones 2 through 6) that reflect current scientific information and harmonize DRBC criteria with basin states' criteria. In addition, a narrative standard applicable to waters of the Basin requires that: "the waters shall be substantially free from … substances in concentrations or combinations which are toxic or harmful to human, animal, plant, or aquatic life".

3.1.3.2 Present Status

For a recent report on the extent to which waters of the Delaware Estuary and Bay are attaining designated uses, see the "2016 Delaware River and Bay Water Quality Assessment". (http://www.state.nj.us/drbc/library/documents/WQAssessmentReport2016.pdf.) Some contaminants identified in the report for additional monitoring and assessment efforts to assure water quality in the Estuary and Basin include metals, pesticides and polycyclic aromatic hydrocarbons (PAHs).

3.1.3.3 Past Trends

Data and detection insufficiencies make determination of past trends difficult. See Chapter 4 - Sediment Quality for information on past trends of contaminants in the Estuary.

3.1.3.4 Future Predictions

With increasingly sensitive analytical methods in use, e.g., inductively coupled plasma mass spectrometry (ICP/MS) to measure contaminants and more complex models to evaluate toxicity, e.g., Biotic Ligand Model (BLM) (Fig 3.1.14), there will be an increasing need for coordination of water quality criteria and assessment methodologies in order to prioritize environmental management efforts.

3.1.3.5 Actions and Needs

Coordination among Basin states and agencies should continue to ensure the use of appropriate analytical techniques and assessment methodologies to evaluate the effects of contaminants on water quality.

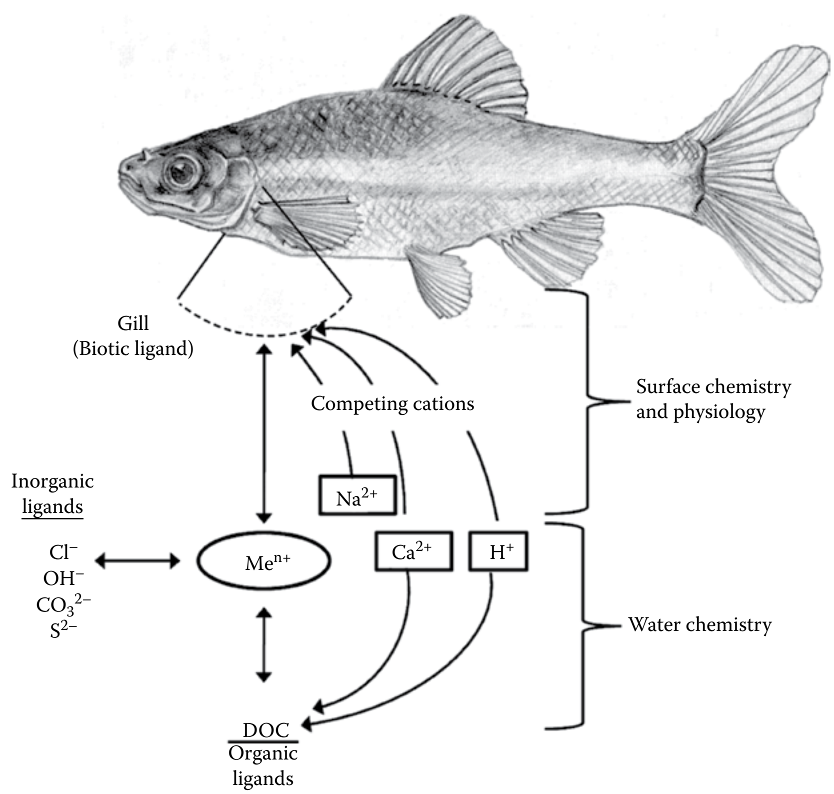

Figure 3.1.14 Conceptual model of the biotic ligand model (after Paquin, P.R. et al., Comp. Biochem. Physiol. C, 133, 3-35, 2002. Art credit Rob Harper, 2009).

3.1.3.6 Summary

Trends for specific contaminants may result from regulatory restrictions on use, changes in loading rates or degradation of the contaminant in the environment, but effective management is needed to maintain water quality and efficiently decrease levels where contaminant levels are elevated.

3.1.4 Fish Contaminant Levels

Certain chemicals tend to concentrate ("bioaccumulate") in fish to levels thousands of times greater than the levels in the water itself. The resulting concentrations in fish and the attendant health risks to those individuals who consume the fish, such as recreational and subsistence anglers, are of concern to government agencies and the public.

3.1.4.1 Description of Indicator

Bioaccumulative contaminants have been monitored over an extended period in fish fillet collected from the Delaware River. Bioaccumulation of contaminants in fish tissue is influenced by physical-chemical properties of the contaminant, fish species, age, migration and food habits as well as other environmental factors such as season of fish collection.

3.1.4.2 Present Status

While programs are in place to reduce the concentrations of toxic pollutants that bioaccumulate, Delaware River Basin states issue "advisories" containing meal advice for consumers of recreationally-caught fish and shellfish to minimize the risk to human health. These advisories list the water bodies, fish species, and number of meals recommended to minimize the risk. In some cases, no consumption of any fish species from a water body or more stringent consumption guidelines for pregnant women and children is advised. These advisories are typically revised yearly based upon recent fish tissue concentration data. A summary of recent fish consumption advisories in the Delaware River is available at http://www.state.nj.us/drbc/library/documents/WQAssessmentReport2016.pdf.

The following websites provide additional information on state-issued fish consumption advisories:

Delaware http://www.dnrec.delaware.gov/fw/Fisheries/Pages/Advisories.aspx

New Jersey http://www.nj.gov/dep/dsr/njmainfish.htm

New York http://www.dec.ny.gov/outdoor/7736.html

Pennsylvania http://www.nj.gov/drbc/quality/datum/fish-consumption.html.

3.1.4.3 Past Trends

A number of bioaccumulative compounds are monitored in fish collected from the Delaware River. Trends will differ depending on the contaminant of interest. Dioxins are examples of toxic chemicals observed in the Delaware River that bioaccumulate in fish. The stream quality objective in the Delaware River is based on the most toxic dioxin compound 2,3,7,8-TCDD. A trend of declining concentrations for 2,3,7,8-TCDD (Dioxin) from 2004 to 2015 with concentrations of the lipophilic contaminant normalized to 5% lipid in fish tissue is graphically presented in Figure 3.1.15 and by an ANCOVA comparison of contaminant concentrations by year with the length of the fish as a covariate in Table 3.1.1. Similar assessments indicate that concentrations of other legacy pesticides (chlordanes and dieldrin) are also declining in some estuarine fish species (not shown).

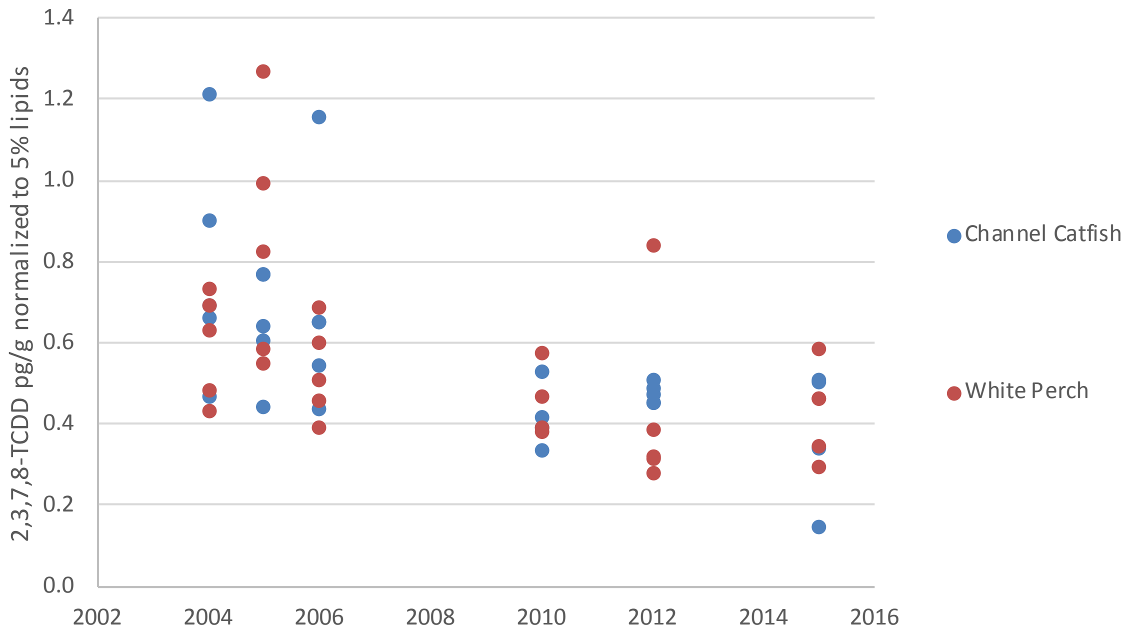

Figure 3.1.15 Concentrations of 2,3,7,8-TCDD in fillet of two tidal fish species by sample year.

3.1.4.4 Future Predictions

Given the hydrophobic and lasting nature of the fish tissue contaminants considered here, it is reasonable to presume that concentrations will remain relatively constantor decline very slowly.. Even the effects of regulatory water quality management efforts will likely take decades to be reflected in tissue concentrations.

3.1.4.5 Actions and Needs

Pollution minimization efforts are necessary to bring about the needed reductions in tissue concentrations. Cooperative efforts among state and federal agencies and other partners to reduce bioaccumulative contaminants in the Delaware River should continue and be expanded to address persistent bioaccumulative and toxic pollutants.

3.1.4.6 Summary

Trends for specific contaminants may result from regulatory restrictions on use, changes in loading rates or degradation of the contaminant in the environment. Trajectories for contaminant reduction in fish may be long depending on the contaminant of concern, but effective management is needed to facilitate these trajectories.

Table 3.1.1 ANCOVA results of year versus contaminant with weight as a covariate

Contaminant	Species	Water	N	Estimate of Slope	p-value	Trend
2,3,7,8 TCDD	Channel Catfish	tidal	28	-0.04	0.0003	declining
2,3,7,8-TCDD	White Perch	tidal	29	-0.02	0.0143	declining

3.1.5 Salinity

The Delaware Estuary is believed to contain one of the largest freshwater tidal prisms in the world and provides drinking water for over one million people. However, salinity could greatly impact the Delaware's suitability as a source for drinking water, if salt water from the ocean encroaches on the drinking water intakes.

3.1.5.1 Description of Indicator

Salinity is usually estimated via direct measurement of other parameters, such as chloride or specific conductivity, with salinity operationally defined in terms of conductivity in standard references such as Standard Methods for the Examination of Water & Wastewater (APHA, AWWA, WEF 2005).

One important metric for understanding the importance of salinity concentrations in the Delaware Estuary is the location of the 250 mg/L chloride concentration based on drinking water quality standards originally established by the U.S. Public Health Service, also known as the "salt line."

The salt line's location fluctuates along the tidal Delaware River as streamflow increases or decreases in response to precipitation, diluting or concentrating chlorides in the River. The seven-day average location of the salt front is used by the DRBC as an indicator of salinity intrusion in the Delaware Estuary. The commission's drought plan focuses on controlling the upstream migration of salty water from the Delaware Bay during low-flow conditions in basin rivers and streams. As higher salinity water moves upstream, it may increase corrosion of the infrastructure of surface water users, particularly industry, and increase the concentration of sodium in treated drinking water which is a health concern for sensitive customers. In the DRBC Water Code Zone 2 location in the Delaware Estuary, where large Pennsylvania and New Jersey drinking water intakes are located, water quality objectives include a maximum 15-day average concentration of 50 mg/L chloride. Salinity repulsion policies, that govern upstream reservoir releases, work to repel the salt line and maintain chloride concentrations below the water quality objective in Zone 2.

Water releases from five reservoirs are used to help dilute the higher salinity water during low streamflow conditions. Three reservoirs — Pepacton, Neversink and Cannonsville— are owned by New York City and are located in the Delaware River's headwaters in the Catskill Mountains in New York State. When full, these three reservoirs hold 271 billion gallons of water. Two additional reservoirs -- Blue Marsh and Beltzville -- are located in Pennsylvania along the Schuylkill River in Berks County and the Lehigh River in Carbon County, respectively. These two lower basin reservoirs hold nearly 20 billion gallons of water when full.

3.1.5.2 Present Status

By combining data from both the Delaware Estuary Water Quality Monitoring Prorgam (formerly the Boat Run) and the University of Delaware water quality cruises, DRBC is able to map the approximate extents of salinity regimes in Delaware Bay. Figure 3.1.16 below shows the approximate polyhaline (> 18 ppt salinity), mesohaline (5 to 18 ppt), and oligohaline (0.5 to 5 ppt) areas, as well as transitional zones. Upstream of the oligohaline is approximately below 0.5 ppt salinity during seasonally normal hydrological conditions, but exceeds the 250 mg/L chloride definition of the salt line during seasonally low streamflow conditions.

Figure 3.1.17 below shows the chloride concentrations from the DRBC Delaware Estuary Water Quality Monitoring Program (formerly Boat Run). A sharp transition between river kilometers 121 and 126 (near Marcus Hook) is evident.

3.1.5.3 Past Trends

To determine whether the recent trends are evident in the DRBC data, we plotted boxplots by year from river kilometer 121 (at the change in spatial structure) and river kilometer 169 (nearest to major drinking water

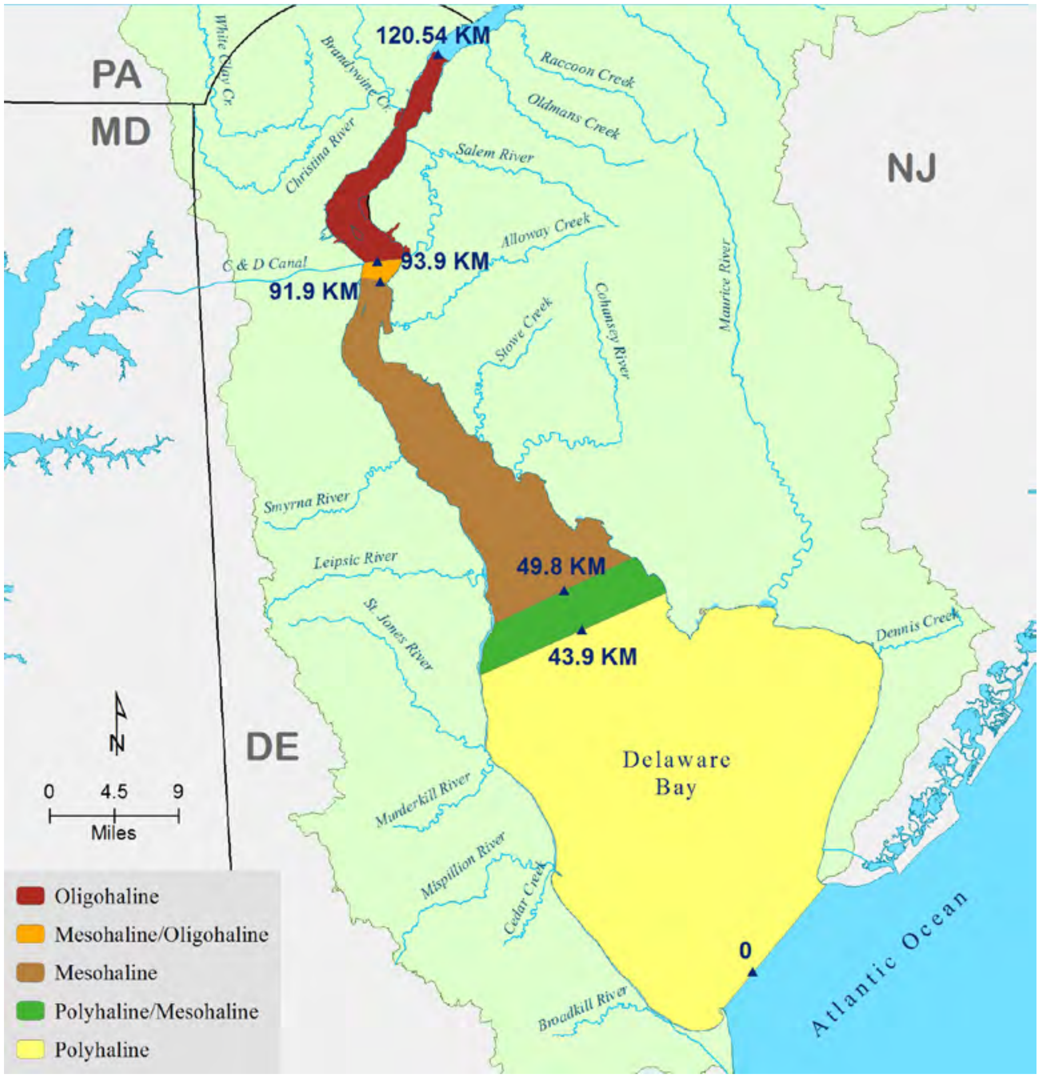

Figure 3.1.16 Spatial salinity regimes of the Delaware Estuary.

intakes). The 2000 to 2016 data at river kilometer 121 (Fig 3.1.18) shows high variability from year to year, but no obvious trend. The same plot for river kilometer 169 (Fig 3.1.19) suggests some slight elevation in 2014 through 2016, but the period of that elevation may be too short to conclude that the data are trending.

The best means of assessing long term historical salinity trends in the estuary is by looking at the long term continuous specific conductivity results collected by the USGS at the Ben Franklin Bridge, Chester, and Reedy Island. At each of those locations, data are available beginning in 1964.

Figures 3.1.20, 3.1.21, and 3.1.22 below suggest that the drought of record in the 1960s strongly influences the oldest data bin. All plots indicate lower conductivity values than the drought of record and year to year variability (especially at Reedy Island). Ben Franklin and Chester both demonstrate distributions over the last year or two that are higher than those of the recent past.

3.1.5.4 Future Predictions

Sea level rise associated with global climate change is expected to change the salinity regime of the Delaware Estuary. A model report prepared by the U.S. Army Engineer Research and Development Center (Kim and Johnson, 2007) shows predicted mean increases in salinity between 1996 and 2040 of 14% at

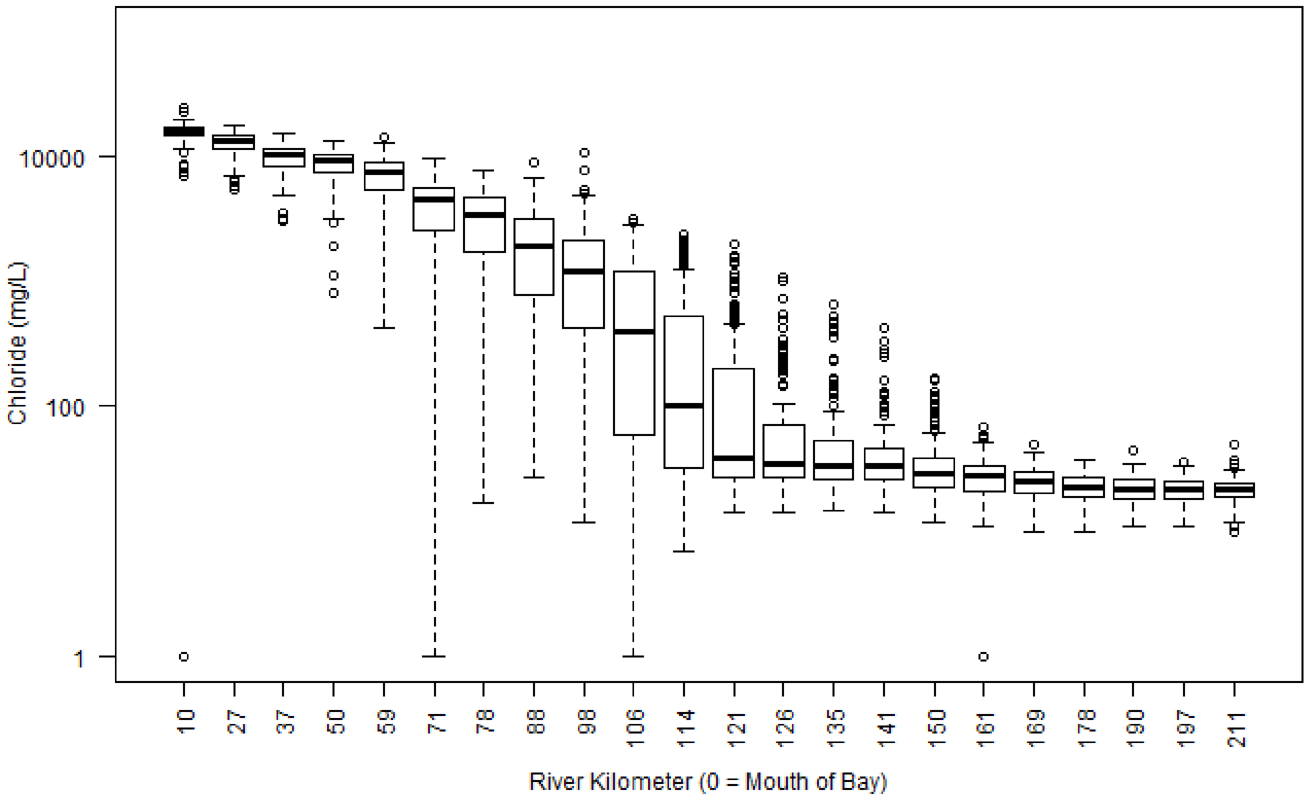

Figure 3.1.17 Chloride concentration ranges by river kilometer in the Delaware Estuary, 2000 through 2016.

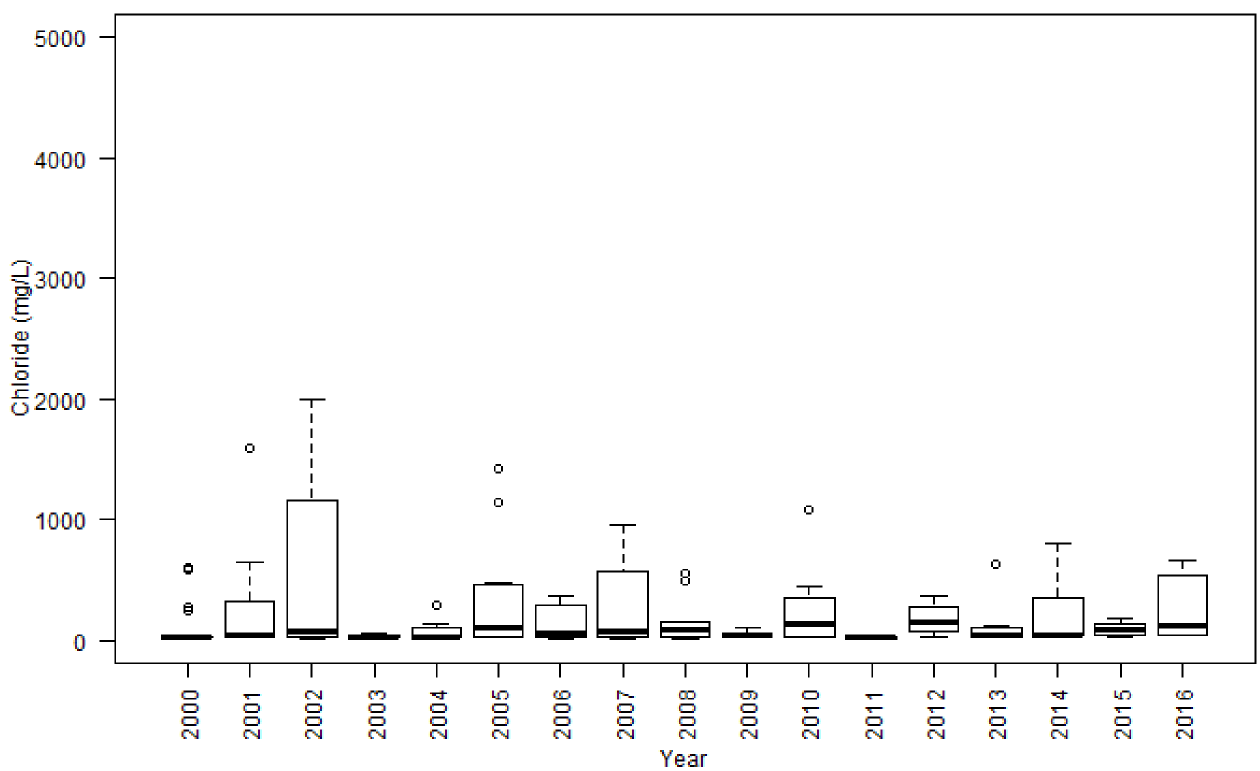

Figure 3.1.18 Recent chloride trends by year at river kilometer 121, 2000 through 2016.

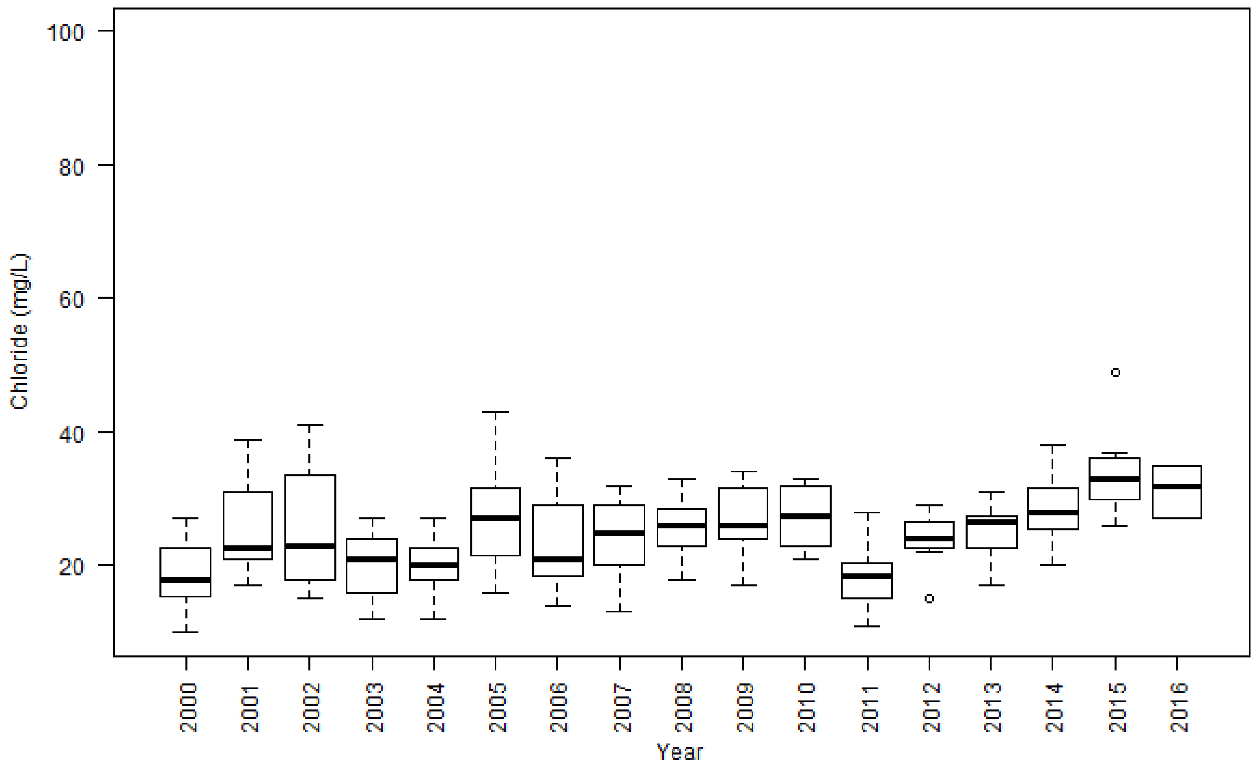

Figure 3.1.19 Recent chloride trends by year at river kilometer 169, 2000 through 2016.

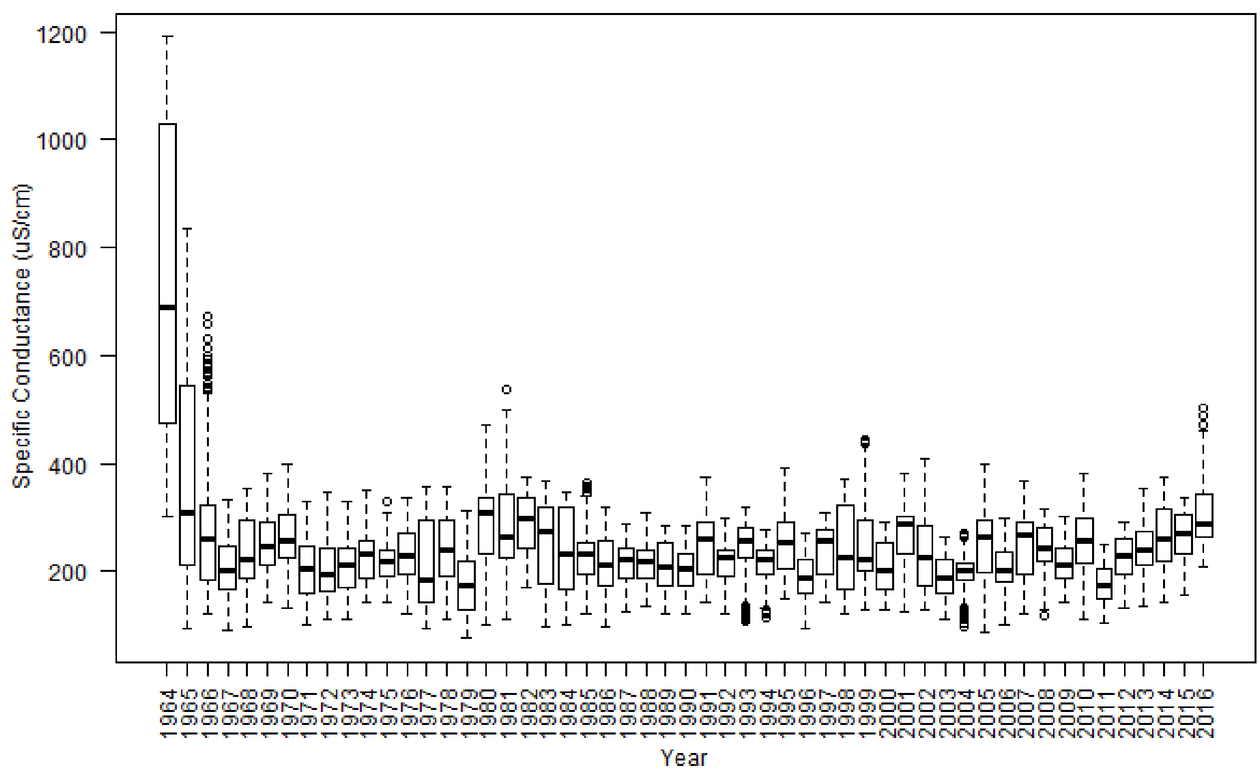

Figure 3.1.20 Long-term specific conductivity box and whisker plots at USGS 01467200, Ben Franklin Bridge.

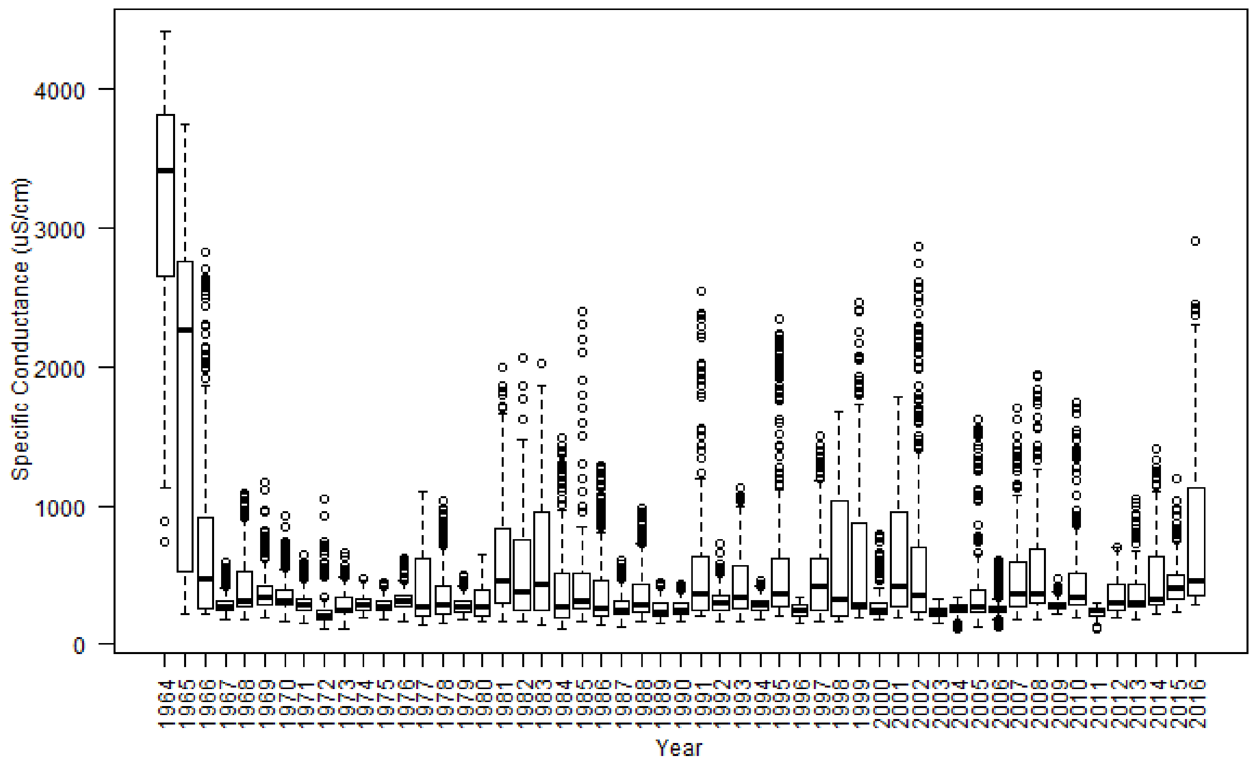

Figure 3.1.21 Long-term specific conductivity box and whisker plots at USGS 01477050, Chester.

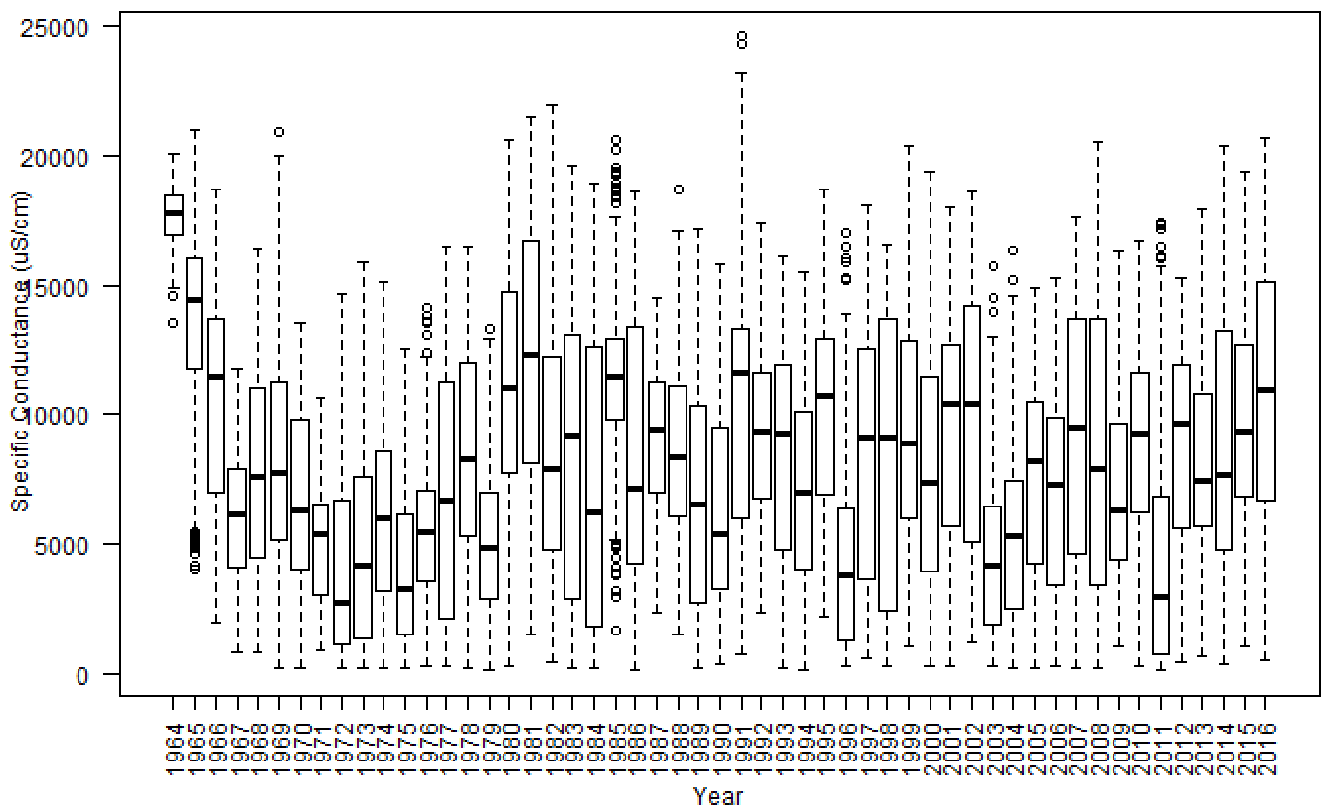

Figure 3.1.22 Long-term specific conductivity box and whisker plots at USGS 1482800, Reedy Island.

Delaware Memorial Bridge, 16% at Chester, PA, and 10% at the Ben Franklin Bridge from sea level rise alone. When combined with other likely drivers, such as channel deepening and changes in consumptive water use over that same period, the forecasted increases in salinity are approximately 22%, 29%, and 18% at the Delaware Memorial Bridge, Chester, and the Ben Franklin Bridge respectively.

3.1.5.5 Actions and Needs

Predictive modeling to establish the linkage between sea level and resultant salinity is needed to assess the expected future salinity spatial regimes. Some level of modeling has been completed and used for this purpose, but longer term forecasts under a wider range of conditions are needed to identify critical conditions and begin to evaluate solutions.

3.1.5.6 Summary

Estuary salinity patterns impact the availability of drinking water and the spatial domains of aquatic living resources. Definitive trends in historic data are not evident from relatively simple assessment tools. Given the importance of the salt line, more refined predictive tools allowing longer term forecasts are needed.

3.1.6 pH

pH is the mathematical notation for the negative log of the hydrogen ion concentration (-log[H+]) and indicates an acid, neutral, or base condition.

3.1.6.1 Description of Indicator

The pH of surface waters can be an important indicator of ecological function and productivity, and pH impacts the bioavailability and toxicity of pollutants such as metals and ammonia. Currently, DRBC's criteria for the Estuary requires pH to be between 6.5 and 8.5.

3.1.6.2 Present Status

Figure 3.1.23 below shows the box and whisker plots of discrete pH values measured at each of the Estuary USGS continuous monitoring stations, compared to the minimum and maximum pH criteria in DRBC's water quality standards. Although the distributions differ by location, all values are within the DRBC criteria.

3.1.6.3 Past Trends

To assess temporal changes in pH, we developed box and whisker plots of pH by year including a dashed blue line at pH=7 for visual reference. Results continue to demonstrate an increase in pH over the period of record at Ben Franklin (Fig 3.1.24) and an even more pronounced increase at Chester (Fig 3.1.25).

This phenomenon was noted in the previous TREB and is likely linked to the gross pollution historically found in the urban corridor of the Delaware Estuary and the remarkable progress at eliminating some of this pollution over the past 40 years. Because human and industrial wastes received little or no treatment through the 1960s and 1970s, the carbonaceous and nitrogenous compounds in these wastes were used as food sources for microbes in the Estuary, which in turn used up the available dissolved oxygen and created an oxygen block around Philadelphia. In addition to using the oxygen, the waste products from this microbial restoration included carbon dioxide and additional hydrogen ions (acids) which historically caused depression of pH that closely mirrored the sag in dissolved oxygen (Culberson 1988). The improved treatment of both municipal and industrial wasted over the past 40 years has therefore been linked to both improvements in dissolved oxygen and pH for the Delaware Estuary, with stronger trends at both the Ben Franklin Bridge and Chester. In addition, this same period has seen the cessation of highly acidic industrial waste inputs to the Delaware Estuary, which may have also contributed to these temporal trends.

3.1.6.4 Future Predictions

NOAA and others have documented the occurrence of ocean acidification. In the absence of other reactions, we might expect the pH to decrease at the ocean boundary, with a corresponding decrease in pH propagated from the ocean into the Estuary. The more complex dynamic of the Estuary, however, suggests that pH levels may be increasing. Further improvements to waste treatment in the urban corridor could lead to further improvements in pH for those freshwater zones of the Estuary. Thus with the processes driving pH in both directions, it is impossible to predict if pH values will continue to rise, level off, or if ocean acidification will pass a tipping point causing pH trends to reverse toward a more acidic Estuary.

3.1.6.5 Actions and Needs

A better understanding of the Estuary carbon cycle and its impact on pH is needed. Models that can integrate the countervailing processes of ocean acidification and decreased microbial respiration could help elucidate the short and long-term likelihoods of continued changes in pH and carbon availability.

3.1.6.6 Summary

Further improvements to waste treatment in the urban corridor could lead to further improvements in pH for those freshwater zones of the Estuary. Thus with the processes driving pH in both directions, it is impossible to predict if pH values will continue to rise, level off, or if ocean acidification will pass a tipping point causing pH trends to reverse toward a more acidic Estuary.

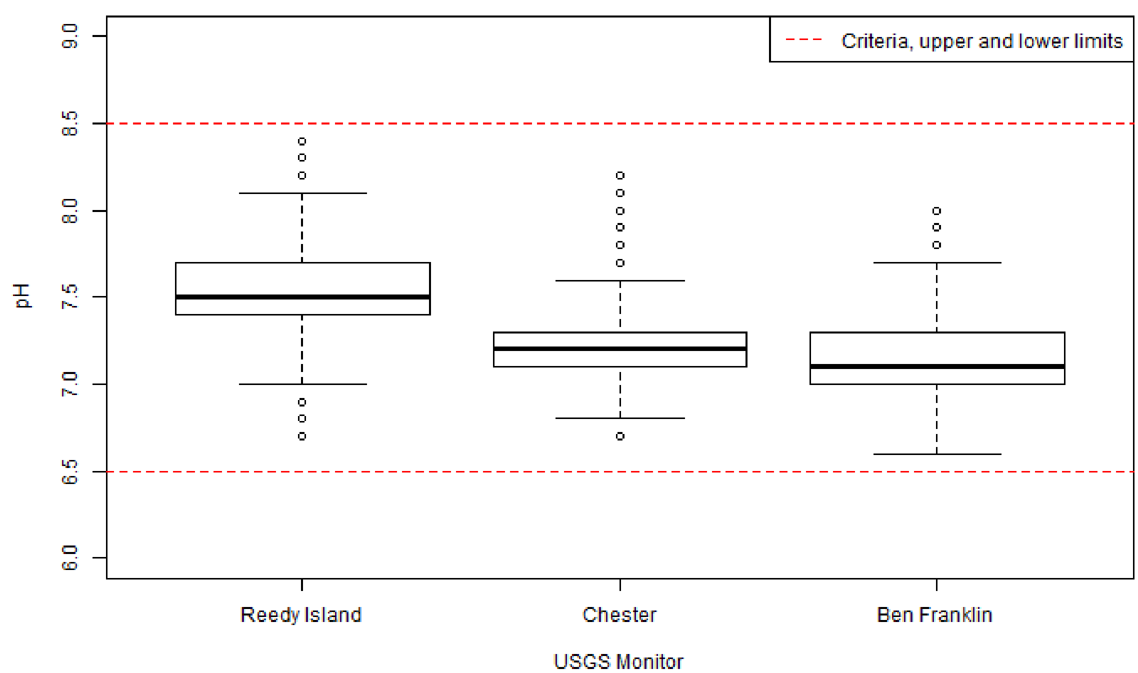

Figure 3.1.23 pH measurements at 3 USGS Delaware Estuary monitors, 2011 through 2016.

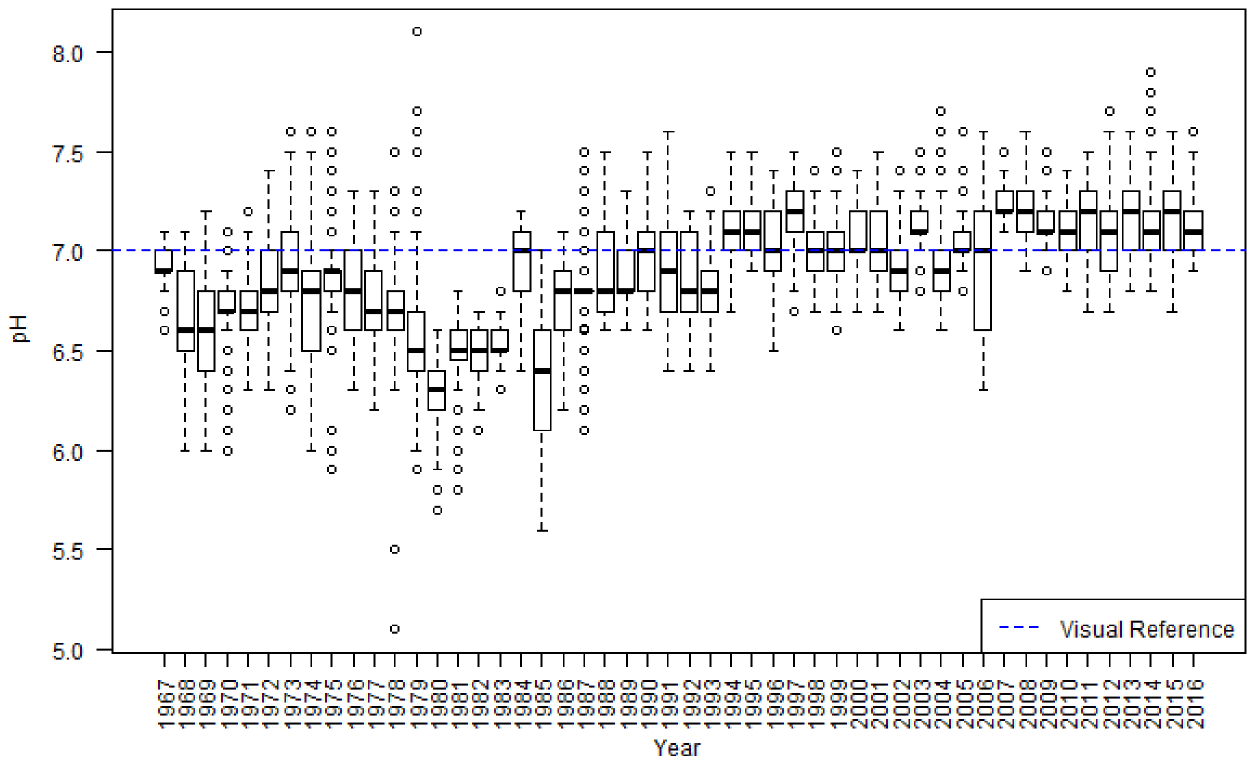

Figure 3.1.24 pH box and whisker plot by year at USGS 01467200, Ben Franklin Bridge, 1967 through 2016.

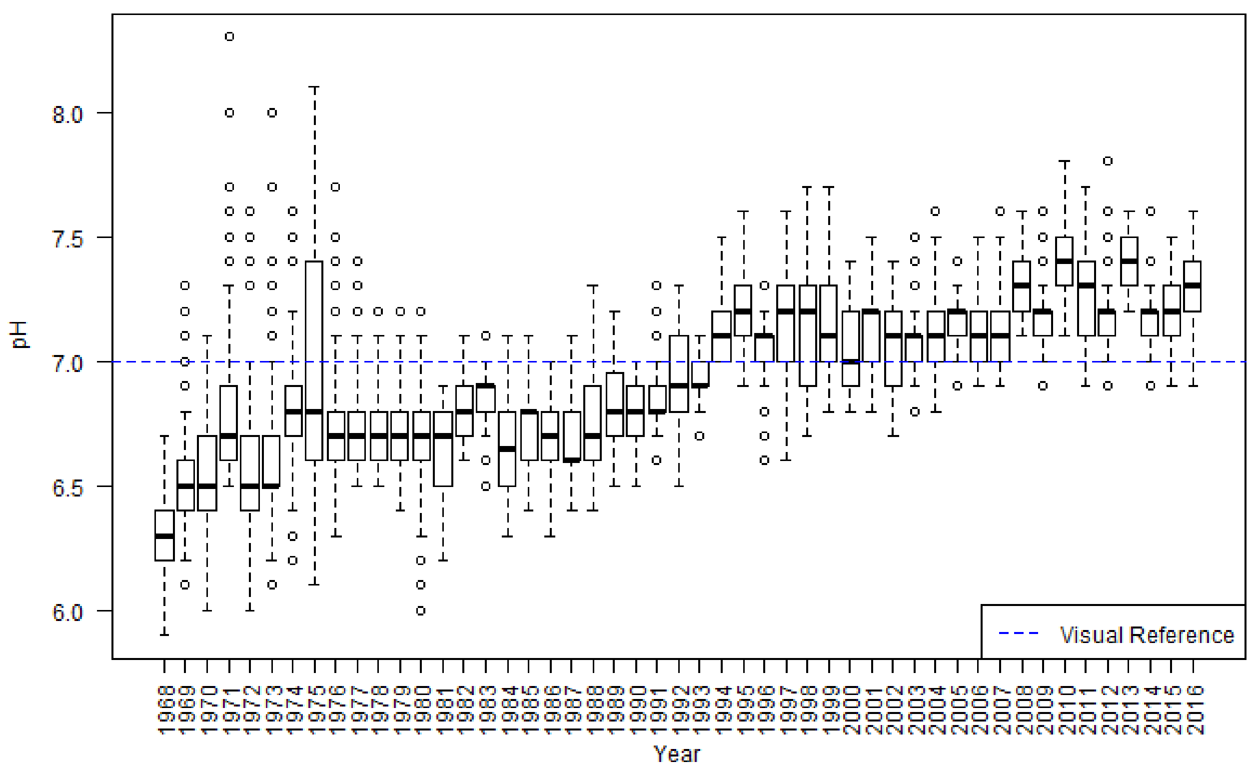

Figure 3.1.25 pH box and whisker plot by Year at USGS 01477050, Chester, 1968 through 2016.

3.1.7 Temperature

3.1.7.1 Description of Indicator

Water temperature is an important factor for the health and survival of native fish and aquatic communities. Temperature can affect embryonic development; juvenile growth; adult migration; competition with non-native species; and the relative risk and severity of disease. Estuary Temperature Criteria are expressed in DRBC regulations by day of year.

Near real-time assessment of temperature criteria in the Delaware Estuary is provided on DRBC's water quality dashboard at http://drbc.net/Sky/waterq.htm, comparing measurements from USGS and NOAA ports monitors to day-of-year temperature criteria.

3.1.7.2 Present Status

Maximum daily water temperatures recorded at USGS continuous monitors at Ben Franklin and Chester from 2011 to 2016 were compared to DRBC's zone specific day-of-year temperature criteria (Fig 3.1.26). Although most observations were below (meeting) criteria, some exceedances were evident.

Determination of the importance of these criteria exceedances is confounded by the strong role played by atmospheric conditions. Work performed for the 2008 Integrated Assessment (http://www.state.nj.us/drbc/08IntegratedList/EntireReport.pdf) suggested that estuary water temperatures were strongly influenced by air temperatures and cloud cover. Brief periods of water temperatures elevated above criteria can have stressful impacts upon aquatic life species, delaying or interrupting spawning, feeding, and development of young. Extremely high temperatures or extended periods above criteria can result in death or detrimental avoidance behavior.

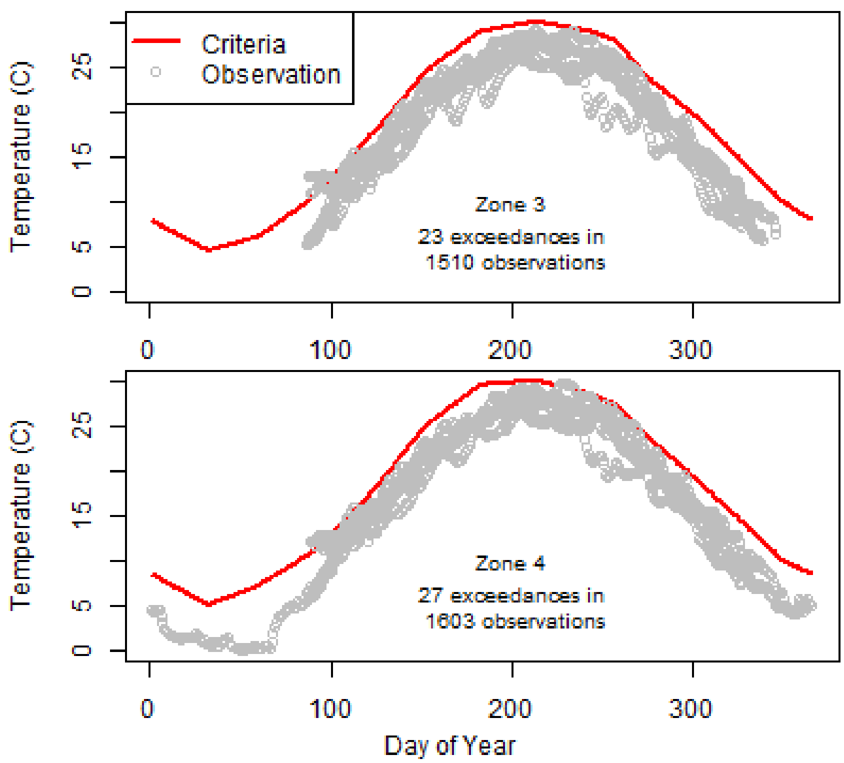

Figure 3.1.26 Temperature observations compared to DRBC day of year criteria, at Ben Franklin and Chester, 2011 through 2016.

3.1.7.3 Past Trends

In the context of global climate change, we want to determine whether water temperatures have changed during the period of observational record. One way to begin this assessment is to investigate whether the temperature has shifted perceptibly during the period of record. Daily mean water temperatures are available from the USGS monitors at the Ben Franklin Bridge (since 1964), Chester (since 1965), and Reedy Island (since 1970). Minimum and maximum daily temperature records extend back slightly further.

For the entire period of record through 2016 for each of the 3 monitors, the median of the mean daily temperature for each day of the year was determined. For example, the daily mean temperature was examined for each May 15th, for every year from the 1960s or 1970, and determined the median of that set. DRBC then compared each May 15th temperature to the median of all May 15th temperatures at that location, to see if the differences changed over time. Figure 3.1.27 shows the mean daily temperature measurements by day of year, and the median for each day of year for the USGS continuous monitor at Chester.

As in the previous TREB, portions of the yearly cycle were examined where broad day to day shifts were minimized (summer and winter). Figures 3.1.28 and 3.1.29 show the residuals (mean daily water temperature – median temperature for that day of year) for Ben Franklin during the summer and Reedy Island during the summer (where the strongest indication for any trend was evident). Consistent with the prior TREB, this analysis suggested a slightly decreasing summer temperature trend at the Ben Franklin station, but an increasing summer temperature trend at the Reedy Island station.

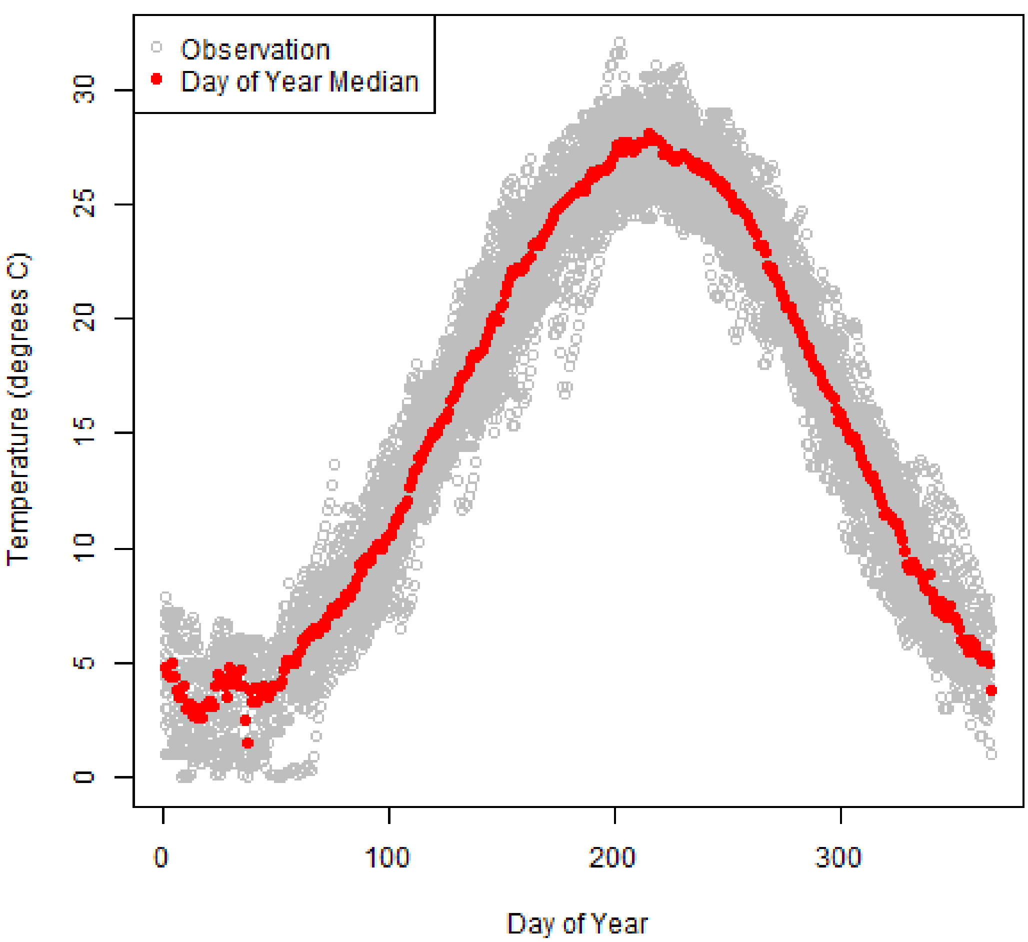

Figure 3.1.27 Period of record temperature observations including median by day of year at Chester, 1964 through 2016.

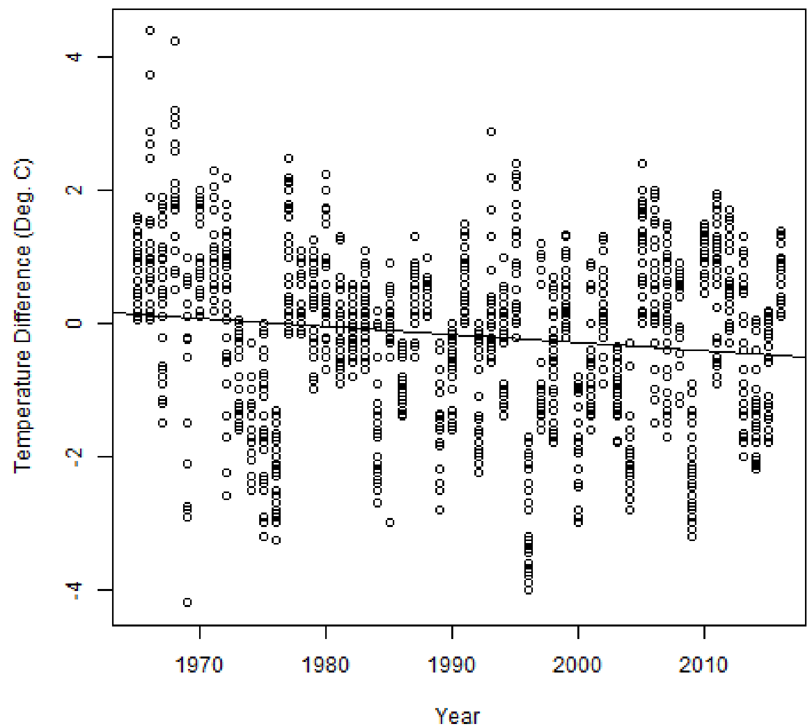

Figure 3.1.28 Delaware River summer residuals at USGS 01467200, Ben Franklin Bridge.

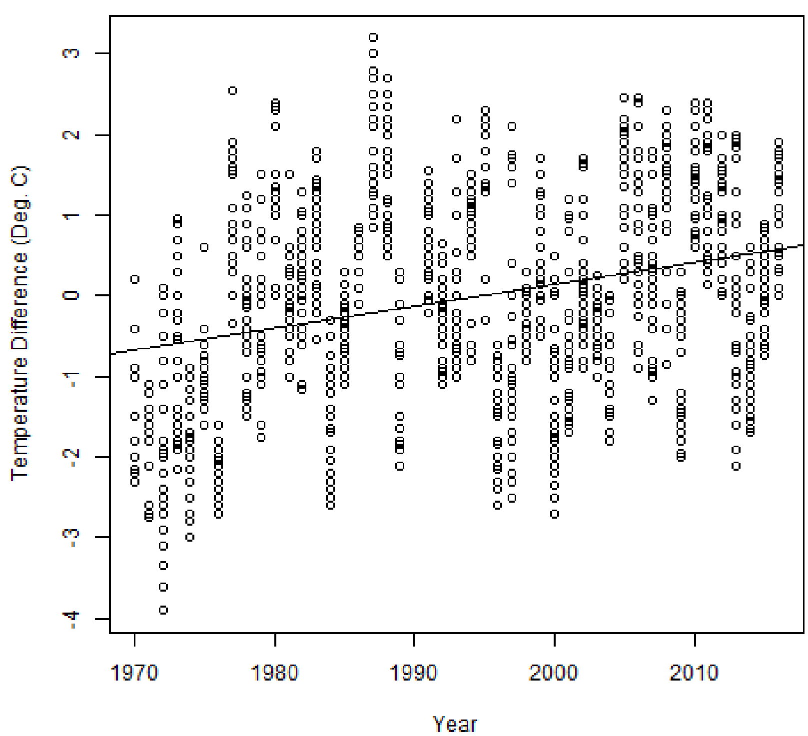

Figure 3.1.29 Delaware River summer residuals at USGS 01482800, Reedy Island Jetty.

As suggested in the previous TREB, these apparently opposite trends could be reflecting different sets of drivers. It seems reasonable to conclude that the Reedy Island increasing temperature trend is reflective of documented climate change, while the Ben Franklin station could be reflecting reductions in industrial thermal loads in the urbanized portion of the Estuary over that same time period.

3.1.7.4 Future Predictions

In their 2008 report, the Union of Concerned Scientists used output from global circulation models to predict that the climate in Pennsylvania would shift toward a climate more similar to Georgia over the next 60 years. Intuitively, this seems to suggest that water temperatures will increase in that same time period. Some temperature drivers, such as sea level rise and shifts in industry and landscape may impose counter-acting forces which cannot be easily estimated.

3.1.7.5 Actions and Needs

In order to gain a firmer understanding of how different temperature drivers are influencing the Delaware Estuary, and ultimately to understand how global climate change may be manifested, a more rigorous evaluation is needed. This evaluation may need to include a temperature model that integrates the various drivers.

3.1.7.6 Summary

Delaware Estuary water temperatures are influenced by multiple drivers including meteorological forces, terrestrial and ocean water inputs, and municipal and industrial thermal loads. A review of the current status shows that 90% or more of daily observations are meeting temperature criteria. An analysis of historic trends suggests that the overlapping temperature drivers make it difficult to understand how water temperatures have changed over the last 5 decades. A more rigorous assessment, which explicitly accounts for overlapping temperature drivers, is desirable.

3.1.8 Emerging Contaminants

Emerging contaminants are substances that have entered the environment through human activities, which may have environmental and ecological consequences. Current regulatory approaches are inadequate to address these contaminants and the increasing public concern over their environmental and human health implications.

3.1.8.1 Description of Indicator

Polybrominated diphenyl ethers (PBDEs) are among the emerging contaminants that have been monitored in the Delaware River. PBDEs are flame retardants used on several consumer products such as television and computer casings and the polyurethane foam inside furniture cushions. They are not chemically bound to the products on which they are used, so they can easily shed off of them and into the environment. There are 209 possible PBDE congeners. PBDE's are characterized as persistent, bioaccumulative, toxic compounds (PBTs). Environmental monitoring programs conducted worldwide during the past decade have shown increasing levels of this emerging contaminant. PBDEs have been detected in the water, sediment, and fish of the Delaware Estuary (Ashley, 2007). Indoor dust is believed to be the primary source of human exposure (82-90%) but dietary exposure is also a concern (USEPA, 2010). Although fish is not a primary source of PBDE exposure, consumption of highly contaminated seafood such as catfish and shellfish have been associated with higher serum PBDE levels (Anderson, 2008).

3.1.8.2 Present Status

Four PBDE congeners are listed on USEPA's Integrated Risk Information System (IRIS): BDE 47, 99, 153, and

209. Toxicity information on IRIS includes Reference Doses (RfDs) for all four congeners for neurobehavioral effects and BDE 209 also has a cancer slope factor (http://www.epa.gov/iris/toxreviews).

3.1.8.3 Past Trends

Emerging contaminants have historically not been routinely monitored therefore limited information is available on past trends. Previous studies by the USEPA, USGS, basin states and private industry on emerging contaminants in the Estuary were identified in the DRBC report titled Emerging Contaminants of Concern in the Delaware River Basin (http://www.state.nj.us/drbc/EmergingContaminantsFeb2007.pdf). However, insufficient data are available to track past trends.

A collaborative project by the DRBC and West Chester University targeting populations that consume fish from the Delaware Estuary evaluated whether there is a declining trend of these four congeners in fish tissue from the Estuary over the years of available data (2004-2012). For each congener, mean lipid-normalized tissue concentrations for each year are presented in line graph form. Sampling sites were combined on the line graphs to show Estuary-wide trends in congener concentrations. Samples were also analyzed by one-tailed Spearman Correlation (on SPSS statistical software) to determine whether fish tissue concentrations demonstrate a significant negative association with sampling year. Declining trends of BDE 209, 153, 99, and 47 in fish tissue were observed. Some fish species have been found to metabolically debrominate certain congeners into other less brominated congeners. Since concentrations of BDE 209, 153, 99, and 47 are less affected by debromination in the catfish, tissue concentration in the catfish may more closely reflect the actual proportions of exposure to each congener. Figure 3.1.30 displays the declining trend in catfish tissue for each of these congeners. All 3 congeners declined 56-59% from their highest measured concentrations (in 2004 or 2005) to their lowest measured concentrations in 2012. BDE 209 levels also showed a moderate, inverse association with sampling year in both catfish ($p=0.045$, $r= -0.327$) and perch ($p=0.014$, $r= -0.403$) (Fig 3.1.31).

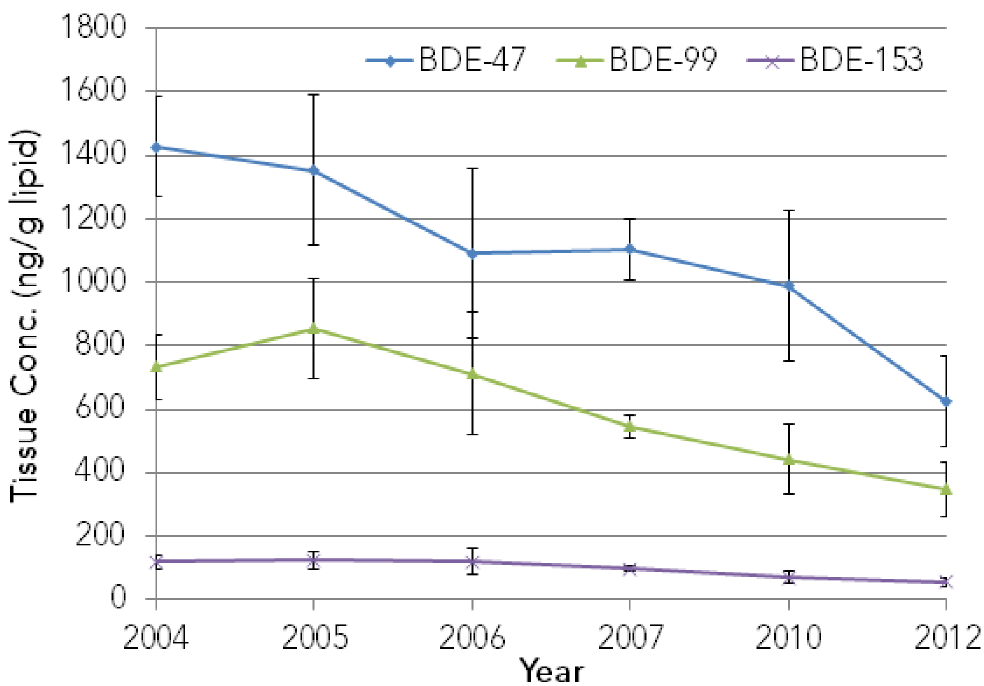

Figure 3.1.30 Lipid normalized tissue concentrations in channel catfish of congeners BDE 47, 99, and 153 by year sampled in Zones 2-5.

3.1.8.4 Future Predictions

While the decline of these congeners in fish tissue is good news and may indicate decreasing environmental contamination by PBDEs, flame retardants currently being used to replace them are not necessarily safe alternatives (Webster, 2012).

3.1.8.5 Actions and Needs

Due to variability of debromination end products by fish species, any future fish surveys should consider common PBDE debromination products in order to assess exposure levels.

Acknowledgement

PBDE trend analysis by Kelly Sand, West Chester University student and her academic advisor Charles V. Shorten, Ph.D., P.E. in collaboration with DRBC staff.

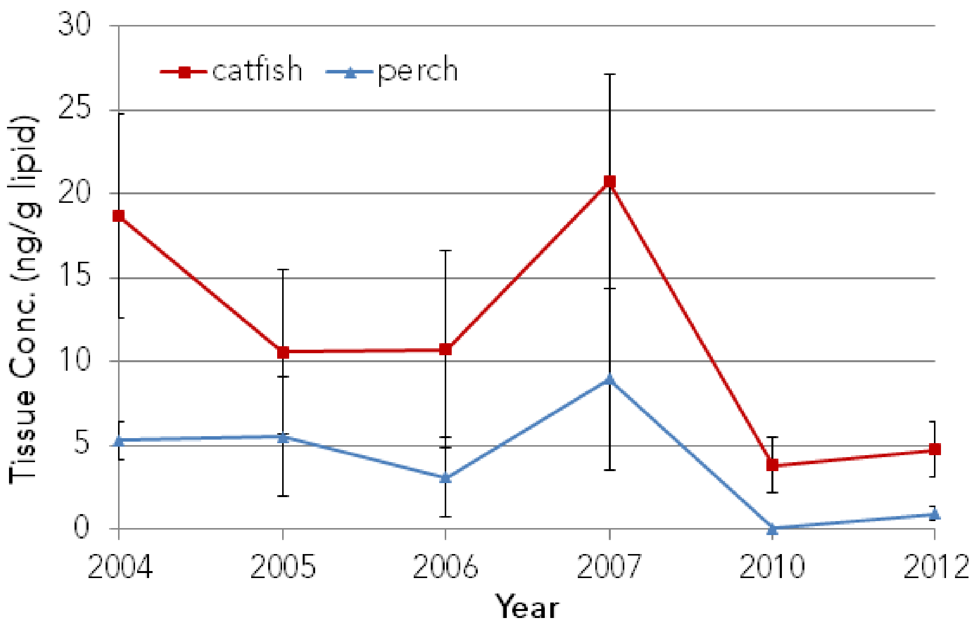

Figure 3.1.31 Lipid normalized tissue concentrations of BDE 209 in channel catfish and white perch by year sampled in Zones 2-5.

3.1.9 Whole Effluent Toxicity

3.1.9.1 Description of Indicator

The tidal Delaware River contains numerous industrial and municipal facilities with National Pollutant Discharge Elimination System (NPDES) effluent discharges (Fig 3.1.32). Whole Effluent Toxicity (WET) testing is a useful approach in the protection of aquatic life by using toxicity tests to measure toxicity of effluents along with the chemical-specific control approach. The two primary advantages to using WET testing over individual chemical-specific controls are: (1) WET tests evaluate the integrated effects of all chemicals in an aqueous sample and; (2) WET tests can measure toxicity caused by other compounds for which a chemical-specific numeric criterion has not been established or do not have an approved parameter specific analytical test method. The WET data used for this trend analysis are of consistent data quality. The trend analysis is based on a chronic toxic unit (TUc) which is (100/IC25) or (100/NOEC) where IC25 is the inhibitory concentration effecting 25% of the test population and NOEC is the no observed effect concentration. Chronic toxicity tests can detect effects at a much lower dose than acute toxicity tests providing a more direct estimate of the safe concentration of effluents in receiving waters. Therefore, chronic toxicity tests have a greater potential to produce more ecologically relevant data.

3.1.9.2 Present Status

Data sets from individual discharges were evaluated by the Mann-Kendall test, a non-parametric statistical procedure. The database was initiated in 1990 as part of the Commission established Toxics Management Program however, data post-2002 was used in the trend analysis because current WET methods were adopted in 2002 and the number of dischargers monitoring for chronic WET increased over time as the monitoring was included in permit renewals and new dockets with most dischargers including biomonitoring after 2002. Of the twelve largest individual dischargers in the Estuary, two dischargers exhibited a decreasing trend for two test species. Four dischargers exhibited a decreasing trend for at least one test species. Six dischargers exhibited no trend. Effluent TUc versus sampling date from 2002 through 2014 for a representative municipal discharge (Fig 3.1.33) and an industry discharge (Fig 3.1.34) are shown.

3.1.9.3 Past Trends

In the 1990s, some dischargers reported toxicity which (estimated after dilution in the receiving water) exceeded the stream quality objective of 1.0 TUc. Available data from recent years do not predict exceedances of stream quality objectives for chronic toxicity by individual dischargers. Determining the cause of a trend is often more difficult than determining the trend. A number of candidates for causes of the observed reduction in chronic toxicity in effluent discharges to the Estuary are efforts by industry to identify and reduce toxicity, pre-treatment and toxics reduction programs for municipal waste treatment facilities, and declining manufacturing in the region.

3.1.9.4 Actions and Needs

Recommendations for future WET monitoring in the Delaware Estuary include continued coordination among the basin states, DRBC and USEPA to generate consistent WET testing throughout the Estuary, and full compliance with WET monitoring by Estuary dischargers. Since the use of a numerical model to predict ambient toxicity from effluent data are complicated by possible additive effects of chronic toxicity, it is recommended that continued efforts be made to monitor not only effluent from discharges but also the ambient environment to ensure that the Delaware River Estuary supports aquatic life from toxicity.

3.1.9.5 Summary

Most effluent discharges to the Delaware Estuary are currently monitored for chronic whole effluent toxicity. The twelve largest dischargers in the Estuary are exhibiting a decreasing trend or no trend in chronic WET data reported for 2002 to 2014. Limiting chronic toxicity in effluents decreases the impact of point source discharges on water quality in the Delaware Estuary. Monitoring for WET for point source discharges in the Delaware Estuary keeps a focus on controlling toxicity in effluents.

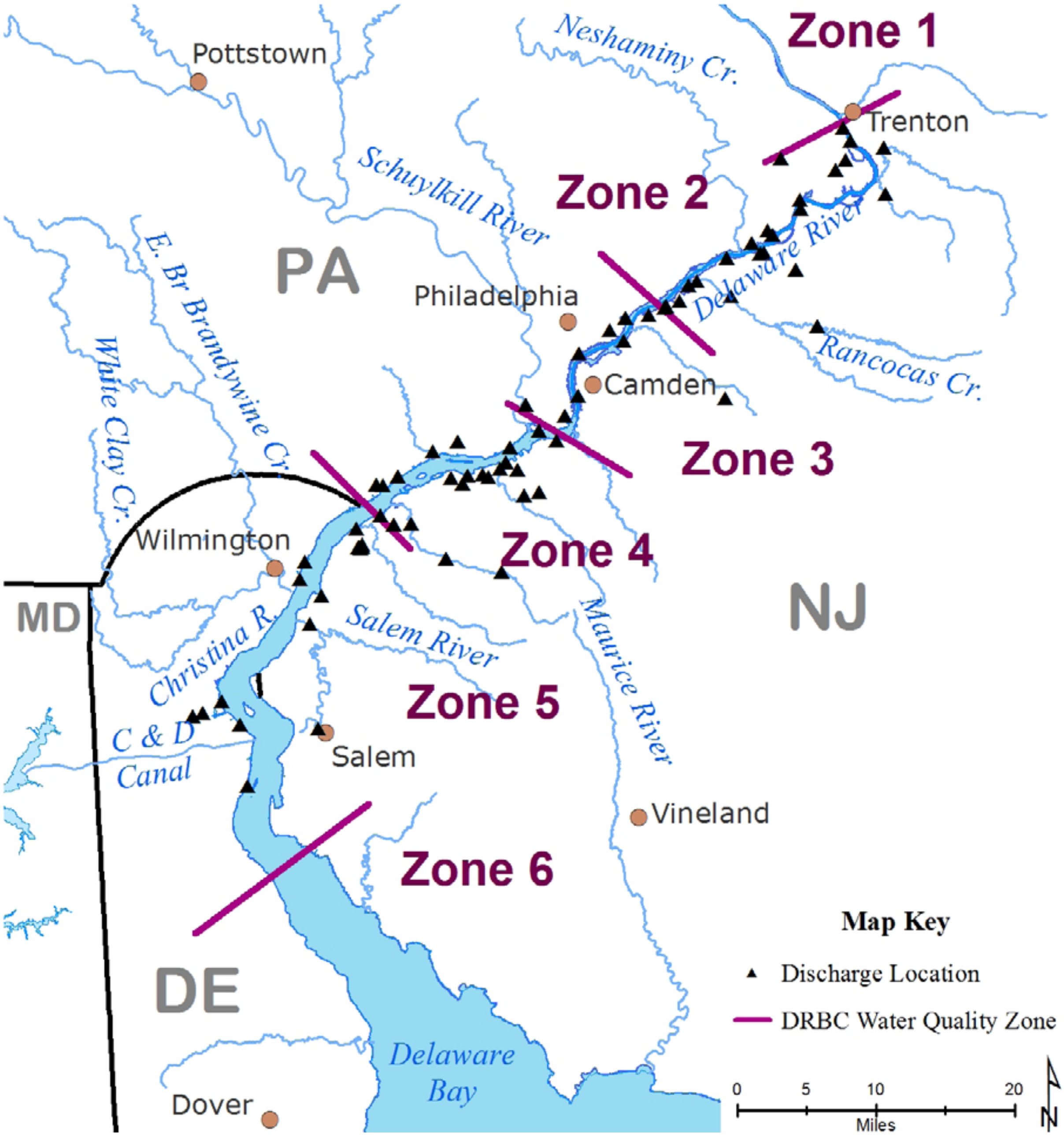

Figure 3.1.32 Delaware Estuary water quality zones and NPDES Discharges.

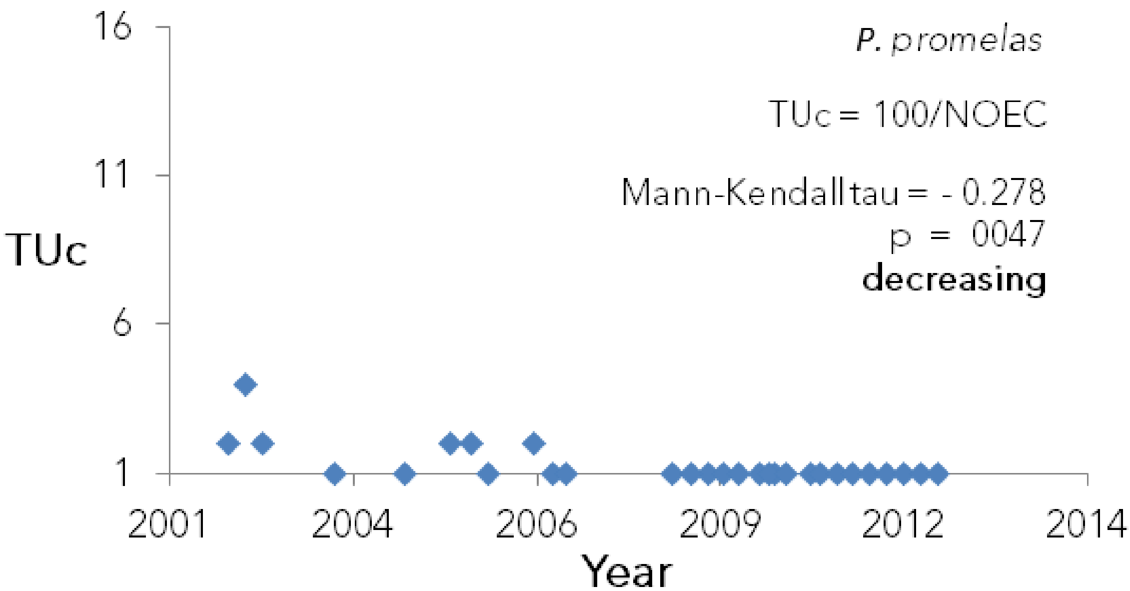

Figure 3.1.33 Municipal Discharge.

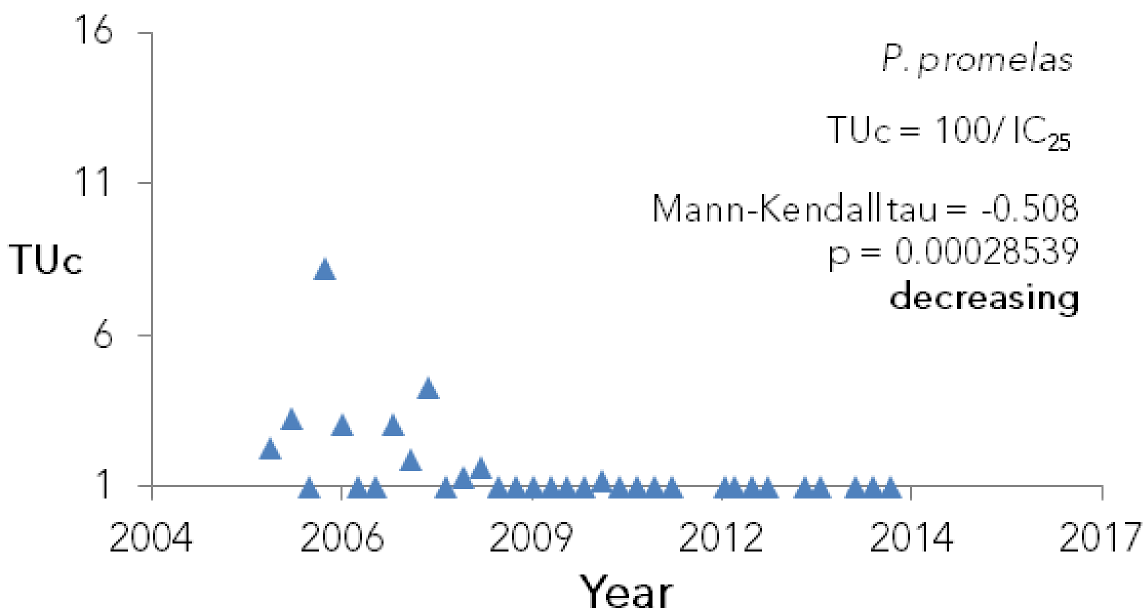

Figure 3.1.34 Industrial Discharge.

3.2 Non-Tidal

3.2.1 Dissolved Oxygen

Dissolved oxygen (DO) refers to the concentration of oxygen gas incorporated in water. Oxygen enters water both by direct absorption from the atmosphere, which is enhanced by turbulence, and as a by-product of photosynthesis from algae and aquatic plants. Sufficient DO is essential to growth and reproduction of aerobic aquatic life. Oxygen levels in water bodies can be depressed by the discharge of oxygen-depleting materials (measured in aggregate as biochemical oxygen demand, BOD, from wastewater treatment facilities), from the decomposition of organic matter including algae generated during nutrient-induced blooms, and from the oxidation of ammonia and other nitrogen-based compounds.

3.2.1.1 Description of Indicator

For our review of oxygen values in the Basin, we looked at two different expressions of DO: concentration, as mg/L, and percent of saturation. DO concentration provides a direct comparison to water quality criteria and to aquatic life affects levels. Percent of saturation gives an indication of the oxygen content relative to saturation due to temperature and salinity.

3.2.1.2 Present Status

We queried the National Water Quality Data Portal for all summer measurements of DO in the Delaware River Basin from 2011 through 2016 and plotted their location and concentration (Fig 3.2.1). This mapping shows the availability of spot measurements and the concentration.

Because DO concentrations are typically characterized by a daily peak in late afternoon and a pre-dawn daily low due to photosynthetic processes, continuous monitors are preferable to daytime spot measurements, which miss the daily low concentrations. In addition, continuous monitors provide a depth and continuity of data that could not be replicated with spot measurements. USGS continuous monitors provide a more complete DO distribution, but at fewer locations. We compared box and whisker plots of summer DO from USGS monitors at the Brandywine at Chadds Ford, the Christina River at Newport DE, the Delaware at Trenton, the Lehigh at Glendon, and the Schuylkill River Vincent Dam (Fig 3.2.2). Although the distributions are different at the different locations, the majority of values are above 5 mg/L (the threshold between fair and poor health identified in the previous TREB).

3.2.1.3 Past Trends

Extended time series data sets are less plentiful in the non-tidal Basin than they are in the Estuary. However, the Delaware River at Trenton has been monitored with a continuous water quality monitor by USGS since 1962. We applied the same time series decomposition technique from earlier in this report to the daily mean DO % of saturation time series at the Delaware at Trenton from 2000 through 2016 to evaluate recent trends (Fig 3.2.3). This analysis suggests high day-to-day variability, resulting in a noisy seasonal pattern, with no apparent trend. Unlike estuary stations, DO at the Delaware at Trenton is strongly influenced by reaeration due to its wide, shallow, high gradient reaches and photosynthesis from attached algae.

3.2.1.4 Future Predictions

Non-tidal DO appears to be relatively stable. Regulatory programs, such as the DRBC's Special Protection Waters regulations are designed to preserve water quality. Where potential DO problems are indicated (such as in Frankford Creek), long term efforts to minimize combined sewer overflows (CSO) are likely to reduce the frequency and magnitude of exceedances over time.

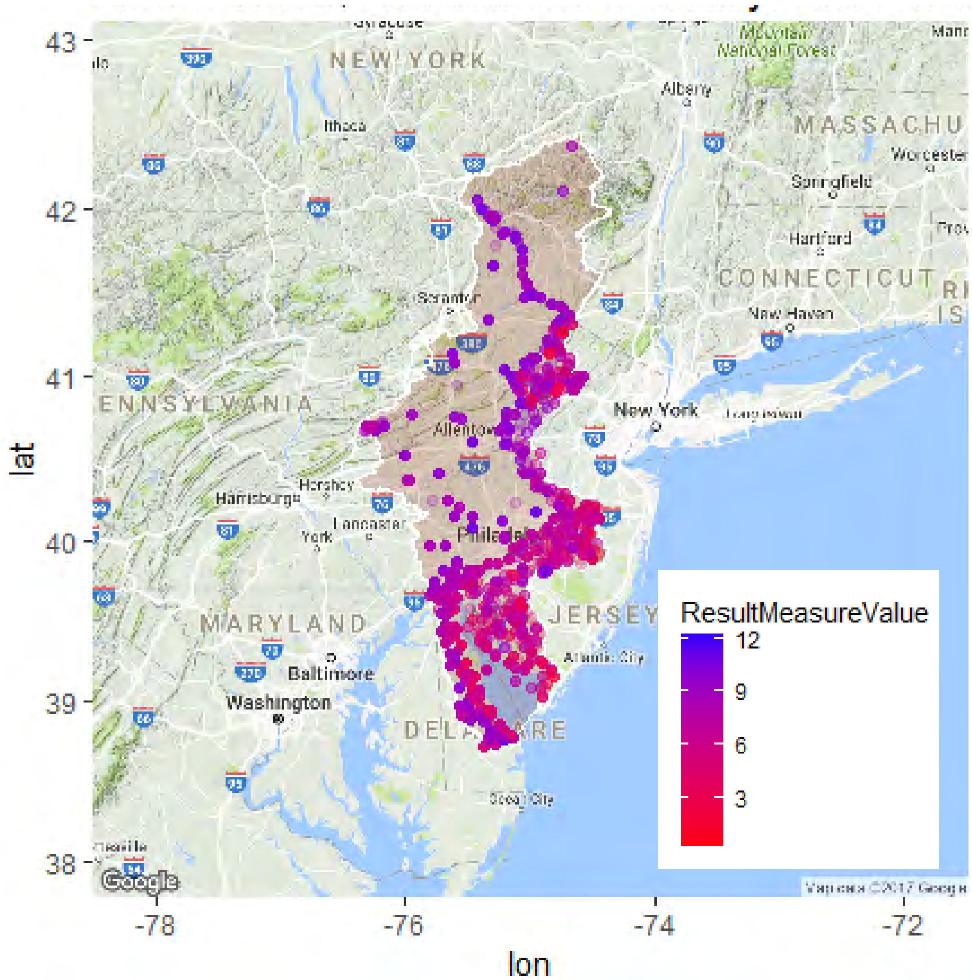

Figure 3.2.2 Summer surface water dissolved oxygen (mg/L) observations in the Delaware River Basin, 2011-2016. From the National Water Quality Data Portal.

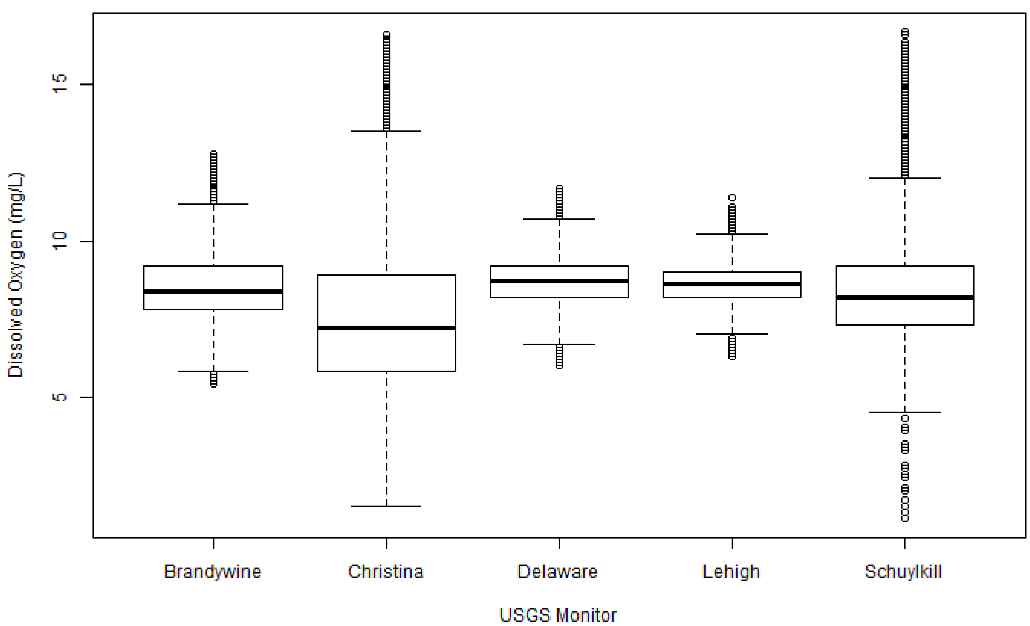

Figure 3.2.1 Box and whisker plot of summer dissolved oxygen (%) from USGS continuous meters in the Delaware Basin, 2011 through 2016.

3.2.1.5 Actions and Needs

Continued monitoring and enhancement of monitoring networks, especially in the realm of continuous real time monitors, will help ensure preservation of water quality and identify reaches where DO is less than optimal.

3.2.1.6 Summary

Available data suggests that DO levels are reasonably good in many locations, with a few areas of localized low DO. The trend at Trenton suggests that DO is stable at relatively high saturation. We expect good dissolved oxygen levels to persist under current regulations, with improvements at impacted sites over the long term. Expansion of continuous real-time monitoring capability in the Basin is recommended.

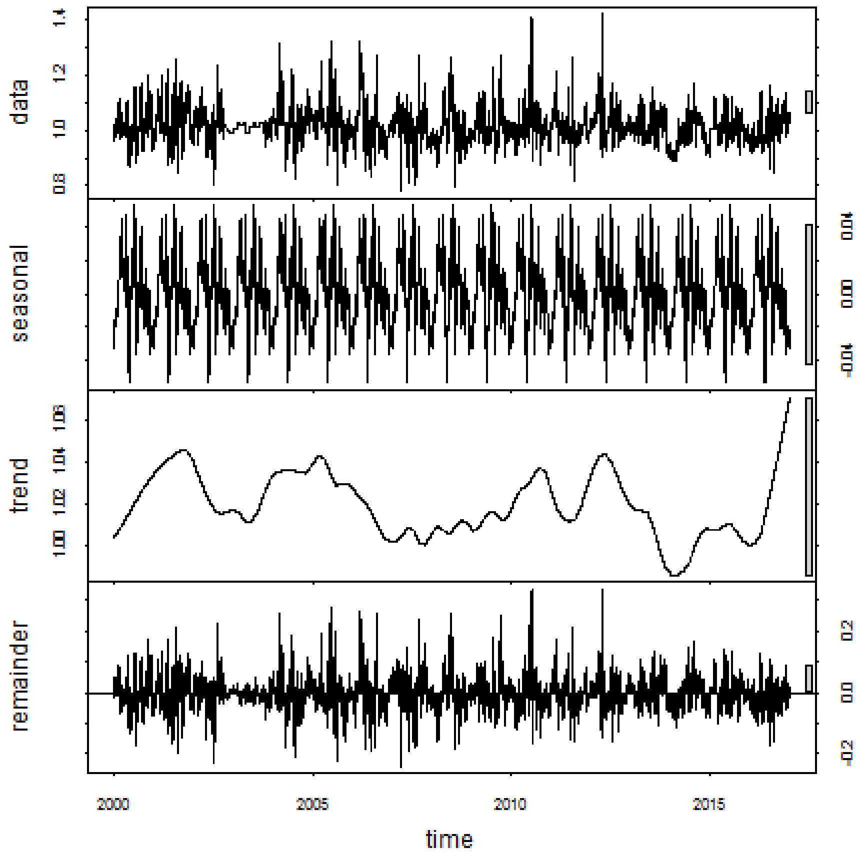

Figure 3.2.3 Time series decomposition, daily dissolved oxygen (%) saturation in the Delaware River, at Trenton, NJ.

3.2.2 Nutrients

A nutrient is any substance assimilated by living things that promotes growth. The term is generally applied to nitrogen and phosphorus, although it can also be applied to trace nutrients like silica and iron. According to USEPA, "High levels of nitrogen and phosphorus in our lakes, rivers, streams, and drinking water sources cause the degradation of these water bodies and harm fish, wildlife, and human health. This problem is widespread—more than half of the water bodies in the United States are negatively affected in some way by nitrogen and phosphorus pollution. (USEPA website: http://water.epa.gov/scitech/swguidance/standards/criteria/nutrients/problem.cfm)

3.2.2.1 Description of Indicator

As part of its Special Protection Waters (SPW) regulations, DRBC has defined Existing Water Quality (EWQ) concentrations of several nutrients including total nitrogen, ammonia, nitrate, total Kjeldahl nitrogen, total phosphorus, and orthophosphate at multiple mainstem Delaware River Boundary Control Points (BCPs) and tributary Interstate Control Points (ICPs). DRBC adopted SPW regulations for Upper and Middle Delaware in 1992, using existing data available at that time to define EWQ, and permanently designated the Lower Delaware as SPW waters in July 2008, using data collected during 2000 through 2004 to define EWQ.

3.2.2.2 Present Status

We queried nitrate and phosphate measurements in surface water in the Delaware River Basin from the National Water Quality Data Portal for the period 2000 through 2015. Locations and results are plotted in Figures 3.2.4 and 3.2.5 below. Figure 3.2.4 suggests relatively lower nitrate concentrations in the upper portion of the Basin, with higher values seen lower in the basin and within the Schuylkill sub-watershed. Figure 3.2.5 suggests low phosphate concentrations in many locations with slightly higher levels seen near the urbanized and Estuary portion of the Basin.

For the nitrate basin map, values were limited to those within the range from the first quantile to the 99th quantile, to minimize the scale impact of outliers.

3.2.2.3 Past Trends

In 2016, DRBC completed a project demonstrating that its Special Protection Waters (SPW) program is effective at keeping clean water clean, and has even allowed improvements in nutrient water quality. DRBC

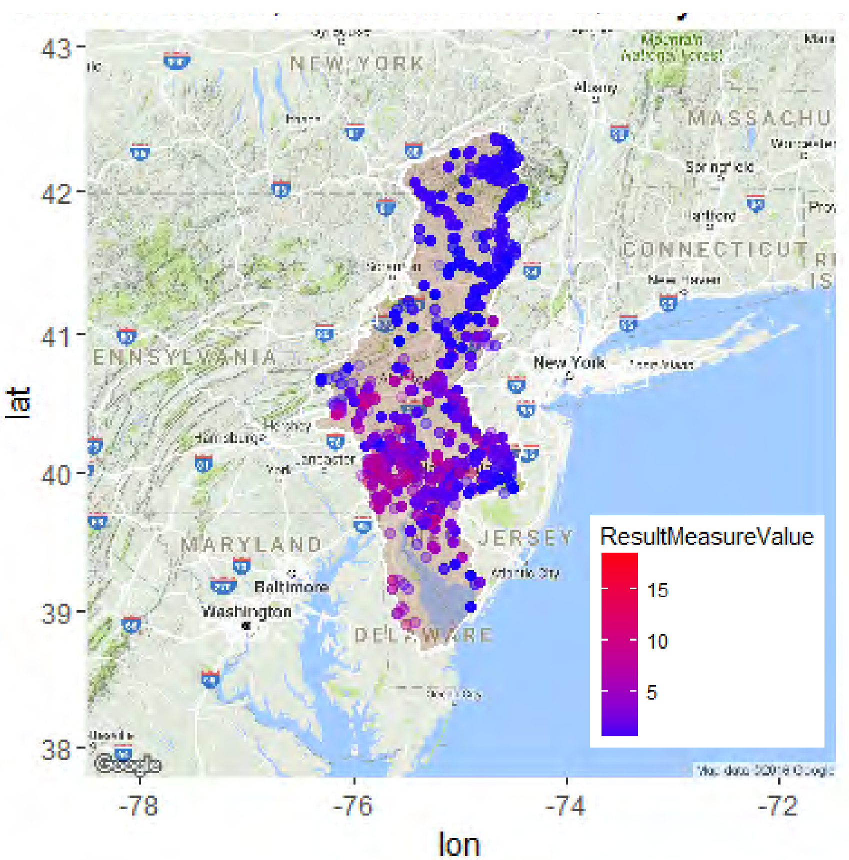

Figure 3.2.4 Surface water nitrate (mg/L) observations in the Delaware River Basin, 2000-2015. From the National Water Quality Data Portal.

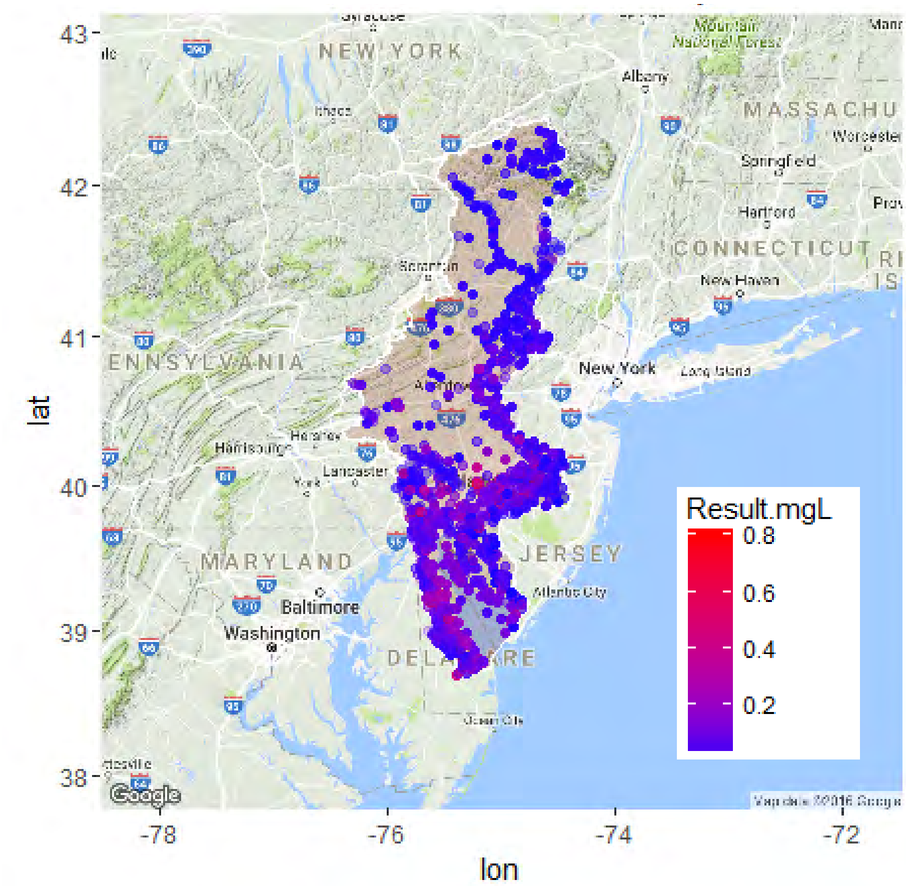

Figure 3.2.5 Surface water phosphate (mg/L) observations in the Delaware River Basin, 2000-2015. From the National Water Quality Data Portal.

compared baseline water quality data initially collected from 2000-2004 to the assessment period of 2009-2011 at 24 sites located on the Delaware River and tributaries. For most water quality parameters at most locations, there were no measurable changes to existing water quality, and nutrient parameters showed improvement at most sites. DRBC's SPW program is designed to prevent degradation where existing water quality is better than the established water quality standards through management and control of wastewater discharges and reporting requirements. Table 3.1.2 below (adapted from the report) shows that all monitoring locations but one demonstrated maintenance or improvement of nutrients for Existing Water Quality. The report and details about the SPW program are available at http://www.nj.gov/drbc/home/newsroom/news/approved/20160808_LDSPW-EWQrpt.html.

For more information on this project contact Robert Limbeck (Robert.Limbeck@drbc.nj.gov).

In 2017 USGS completed an assessment of long term trends in water quality in New Jersey, including stations on the Delaware River and within the Basin. This assessment corroborates nutrient improvements in the non-tidal Delaware River. That report is available at https://pubs.er.usgs.gov/publication/sir20165176

3.2.2.4 Future Predictions

USEPA has prioritized nutrient criteria development in the United States for over 15 years, with states, interstates, and tribes serving as the lead agencies for understanding how nutrients function in their aquatic systems and what nutrient loadings and/or concentrations are needed to sustain healthy biological

Table 3.1.2 Results of existing water quality assessment for nutrients.

Site Name	Nitrogen (mg/L)				Phosphorus (mg/L)	
	Ammonia Nitrogen, Total	Nitrate + Nitrite, Total	Nitrogen, Total (TN)	Kjeldahl, Total (TKN)	Ortho-phosphate, Total	Phosphorus, Total (TP)
Delaware River at Trenton						
Delaware River at Washingtons Crossing						
Pidcock Creek, PA						
Delaware River at Lambertville						
Wickecheoke Creek, NJ						
Lockatong Creek, NJ						
Delaware River at Bulls Island						
Paunacussing Creek, PA						
Tohickon Creek, PA						
Tinicum Creek, PA						
Nishisakawick Creek, NJ						
Delaware River at Milford						
Cooks Creek, PA						
Musconetcong River, NJ						
Delaware River at Riegelsville						
Pohatcong Creek, NJ		**	**			
Lehigh River, PA						
Delaware River at Easton						
Bushkill Creek, PA						
Martins Creek, PA						
Pequest River, NJ						
Delaware River at Belvidere						
Paulins Kill River, NJ						
Delaware River at Portland						

Key

(grey)	No indication of measurable change to EWQ
** (orange)	Indication of measurable water quality change toward more degraded status

conditions long-term. As this effort to develop criteria comes to fruition, it is reasonable to presume that some subset of tributaries will be above criteria, and actions will be taken to remedy the exceedances. Thus it is reasonable to expect some continued modest decrease in nutrient concentrations.

3.2.2.5 Actions and Needs

The most important actions needed are the completion of the assessment to determine if EWQ has been maintained at BCPs and ICPs. In addition, the continued development of numerical nutrient criteria is needed to ensure ecological health of basin waters.

3.2.2.6 Summary

The Assessment of Existing Water Quality performed by DRBC in 2016 suggests that at most of the locations evaluated for most nutrient parameters, conditions are being maintained or improving. The USGS assessment completed in 2017 corroborates these findings for the non-tidal Delaware River in New Jersey.

3.2.3 Contaminants

The "Contaminants" indicator is a general category for specific elements and compounds varying degrees of toxicity to aquatic life and human health.

3.2.3.1 Description of Indicator

Water quality monitoring data from multiple organizations (DRBC, DNREC, NYSDEC, NJDEP, PADEP and USGS) are included in water quality assessments of the Delaware River including data from DRBC enhanced studies of non-tidal (Zone 1) metals. Toxic pollutants data are collected using USEPA approved or equivalent methods with the level of monitoring varying by Zone and toxic pollutant.

3.2.3.2 Present Status

To ensure attainment and maintenance of downstream water quality standards and to facilitate consistent and efficient implementation and coordination of water quality-related management actions in shared interstate waters protected for public water supply, the most stringent ambient water quality criteria for human health for New York or Pennsylvania are compared to surface water data in in non-tidal DRBC Water Quality Management Zones Zones 1A and 1B. The most stringent ambient water quality criteria for human health for Pennsylvania or New Jersey is compared to surface water data in non-tidal DRBC Water Quality Management Zones Zones 1C, 1D, and 1E. For waters protected for use by fish and other aquatic life, the most stringent ambient water quality criteria apply in non-tidal shared interstate waters. The report "2016 Delaware River and Bay Water Quality Assessment" describes concerns for the support of human health due to PCB and mercury concentrations and the need for further evaluation of aluminum, cadmium and copper in non-tidal segments of the river. (http://www.state.nj.us/drbc/library/documents/WQAssessmentReport2016.pdf)

3.2.3.3 Past Trends

Data and detection insufficiencies make determination of past trends difficult.

3.2.3.4 Future Predictions

As monitoring and assessment procedures are refined, and criteria updated to reflect current research, appropriate end points can be defined along with the non-tidal zone contaminant concentrations relative to those endpoints. In the face of improving management, it is reasonable to expect improvements in water quality and declines in concentrations of priority pollutants; however it is more likely that levels will remain relatively the same at their current levels. Although some upward pressure is likely to be exerted by population growth, these influences may be more than countered by economic shifts and effective water quality management.

3.2.3.5 Actions and Needs

Continuity in monitoring programs, continued assessments, and continued updates in criteria are all needed to maintain water quality and effectively decrease levels where levels are elevated. Additional monitoring and assessment of toxic contaminants in the non-tidal portion (Zone 1) of the Delaware River is recommended.

3.2.3.6 Summary

Trends for specific contaminants may result from regulatory restrictions on use, changes in loading rates or degradation of the contaminant in the environment, but effective management is needed to maintain water quality and efficiently decrease levels where contaminant levels are elevated.

3.2.4 Fish Contaminant Levels

Certain chemicals tend to concentrate ("bioaccumulate") in fish to levels thousands of times greater than the levels in the water itself. The resulting concentrations in fish and the attendant health risks to those individuals who consume the fish, such as recreational and subsistence anglers, are of concern to government agencies and the public.

3.2.4.1 Description of Indicator

Bioaccumulative contaminants have been monitored over an extended period in fish fillet collected from the Delaware River. Bioaccumulation of contaminants in fish tissue is influenced by physical-chemical properties of the contaminant, fish species, age, migration and food habits as well as other environmental factors such as season of fish sampling.

3.2.4.2 Present Status

While programs are in place to reduce the concentrations of toxic pollutants that bioaccumulate, Delaware River Basin states issue "advisories" containing meal advice for consumers of recreationally-caught fish and shellfish to minimize the risk to human health. These advisories list the water bodies, fish species, and number of meals recommended to minimize the risk. In some cases, no consumption of any fish species from a water body or more stringent consumption guidelines for pregnant women and children is advised. These advisories are typically revised yearly based upon recent fish tissue concentration data. A summary of fish consumption advisories in the Delaware River is available at http://www.state.nj.us/drbc/library/documents/WQAssessmentReport2016.pdf.

The following websites provide additional information on state-issued fish consumption advisories:

Delaware http://www.dnrec.delaware.gov/fw/Fisheries/Pages/Advisories.aspx

New Jersey http://www.nj.gov/dep/dsr/njmainfish.htm

New York http://www.dec.ny.gov/outdoor/7736.html

Pennsylvania http://www.nj.gov/drbc/quality/datum/fish-consumption.html.

3.2.4.3 Past Trends
A number of bioaccumulative compounds are monitored in fish collected from the Delaware River. Trends will differ depending on the contaminant of interest. Dioxins are examples of toxic chemicals observed in the Delaware River that bioaccumulate in fish. The stream quality objective in the Delaware River is based on the most toxic dioxin compound 2,3,7,8-TCDD. A slight declining trend in White Suckers and no trend in Smallmouth Bass of concentrations for 2,3,7,8-TCDD (Dioxin) from 2004 to 2015 with concentrations of the lipophilic contaminant normalized to 5% lipid in fish tissue is graphically presented in Figure 3.2.6 and by an ANCOVA comparison of contaminant concentrations by year with the length of the fish as a covariate in Table 3.2.1. Similar assessments indicate that concentrations of other legacy pesticides (chlordanes and dieldrin) are not indicating a trend in non-tidal fish species (not shown).

3.2.4.4 Future Predictions
Given the hydrophobic and lasting nature of many fish tissue contaminants, it is reasonable to presume that concentrations will remain relatively constant. For many compounds, even the effects of regulatory water quality management efforts will likely take decades to be reflected in tissue concentrations.

3.2.4.5 Actions and Needs
Pollution minimization efforts are necessary to bring about the needed reductions in tissue concentrations. Cooperative efforts among state and federal agencies and other partners to reduce emissions of bioaccumulative contaminants to the Delaware River should continue and be expanded.

3.2.4.6 Summary
Trends for specific contaminants may result from regulatory restrictions on use, changes in loading rates or degradation of the contaminant in the environment. Trajectories for contaminant reduction in fish may be long depending on the contaminant of concern, but effective management is needed to facilitate these trajectories.

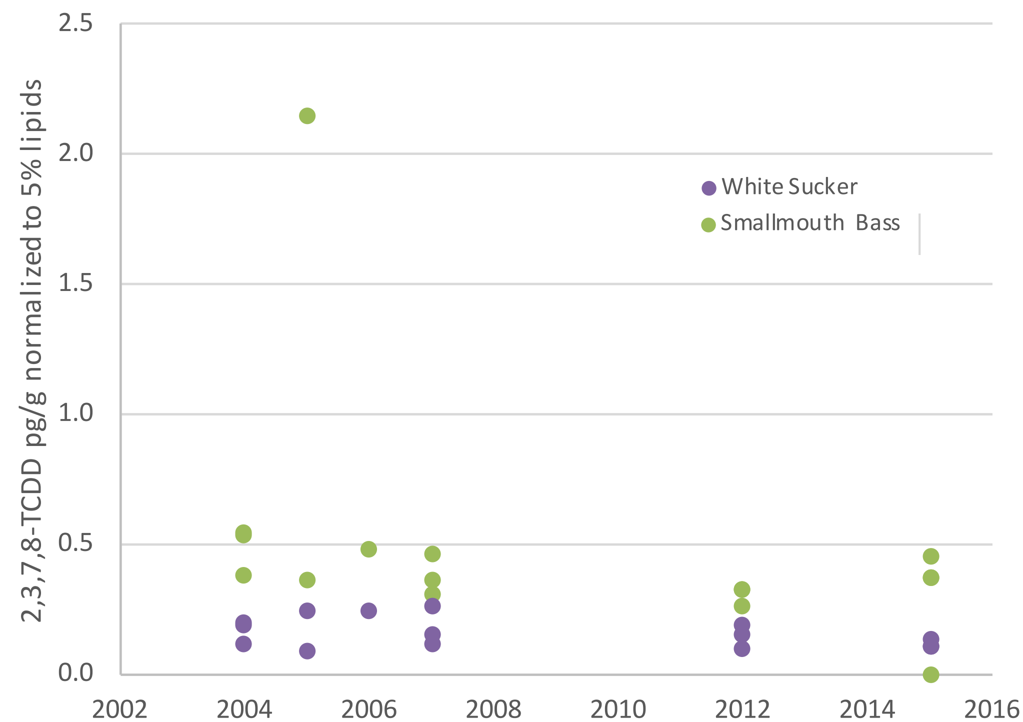

Figure 3.2.6 Concentrations of 2,3,7,8-TCDD in fillet of two non-tidal fish species by sample year.

Table 3.2.1 ANCOVA results of year versus contaminant with weight as a covariate.

Contaminant	Species	Water	N	Estimate of Slope	p-value	Trend
2,3,7,8 TCDD	Smallmouth Bass	non-tidal	6	-0.03	0.40	none, slight
2,3,7,8-TCDD	White Sucker	non-tidal	2	-0.0016	0.02	declining

3.2.5 Emerging Contaminants

Emerging contaminants are unregulated substances that have entered the environment through human activities, which may have environmental/ecological consequences. Current regulatory approaches are inadequate to address these contaminants and the increasing public concern over their environmental and human health implications.

3.2.5.1 Description of Indicator

Pharmaceuticals and Personal Care Products (PPCP) include a wide suite of active ingredients in prescription and over-the-counter medication such as antibiotics, anti-inflammatories and anti-hypertensives as well as personal care products such as anti-bacterials. Concentrations of PPCPs have been shown to be generally higher in urbanized and industrialized areas.

3.2.5.2 Present Status

A recent collaborative research project was carried out by Temple University and the DRBC to increase our understanding of the loading of emerging contaminants by sampling tributaries in a specific area of the Delaware River watershed that is urbanized and significantly impacted by wastewater treatment plant effluents. Fifteen target compounds were selected for analysis based on their frequency of detection in a previous multiyear study conducted on the Delaware River main stem. The analytes measured in surface water included clarithromycin, trimethoprim, carbamazepine, diphenhydramine, dehydronifedipine, diltiazem, erythromycin, gemfibrozil, ibuprofen, triclocarban, metformin, guanylurea, ranitidine, sulfamethoxazole and thiabendazole. Ten sampling sites were chosen on tributaries receiving municipal and industrial discharges. Tributaries sampled were East Perkiomen Creek, Perkiomen Creek, Schuylkill River, Wissahickon Creek and Neshaminy Creek. Sampling locations were above and below potential source discharges. Sampling was designed to assess seasonal differences in emerging contaminant loadings. The measured environmental concentrations of the target compounds present a detailed picture of urban and industrial impacts on subwatershed receiving waters. An "index of concern" ranking system is in development for the sample locations by comparing measured environmental concentrations, existing target compound water quality criteria or predicted no effects levels and developing a concern summary parameter.

3.2.5.3 Actions and Needs

Because of concerns about potential effects of PPCP on aquatic life, future work should evaluate the sources as well as the fate and effects of PPCP in the Delaware River water column, sediments and biota.

3.2.6 pH

pH is the mathematical notation for the negative log of the hydrogen ion concentration (-log[H+]) and indicates an acid, neutral, or base condition.

3.2.6.1 Description of Indicator

The pH of surface waters can be an important indicator of ecological function and productivity, and pH impacts the bioavailability and toxicity of pollutants such as metals and ammonia. Currently, DRBC's criteria for the Delaware River requires pH to be between 6.5 and 8.5.

3.2.6.2 Present Status

Boxplots of summer pH from USGS monitors at the Brandywine at Chadds Ford, the Christina River at Newport DE, the Delaware at Trenton, and the Lehigh at Glendon from 2011 through 2016 show different distributions in pH by location (Fig 3.2.7). Since pH can react to productivity, summer was selected to capture this influence.

DRBC's criteria for the Delaware River requires pH to be between 6.5 and 8.5. Figure 3.2.8 below shows the boxplot of pH instantaneous measurements by year at the Delaware River at Trenton from 2008 through 2016. The applicable criteria are plotted as red lines, and the plot shows that during many years, as many as 25% of the measured values exceed the upper limit criteria of pH = 8.5. Exceedances of the criteria are permissible when due to natural conditions, but more work is needed to evaluate what proportion of these exceedances are attributable to natural conditions. Some criteria violations are attributable to high pH conditions during periods of high primary production, although nutrients concentrations may contribute to the frequency and magnitude of pH exceedances through stimulation of algae and aquatic plants.

3.2.6.3 Past Trends

We developed a box plot of the daily median pH values at the Delaware River at Trenton by year for the period 2000 through 2016, shown in Figure 3.2.9 below. No clear trend is indicated.

3.2.6.4 Future Predictions

Observations of pH appear to be relatively stable in the non-tidal portion of the Basin. Continued stable pH, within the already observed ranges, seems likely.

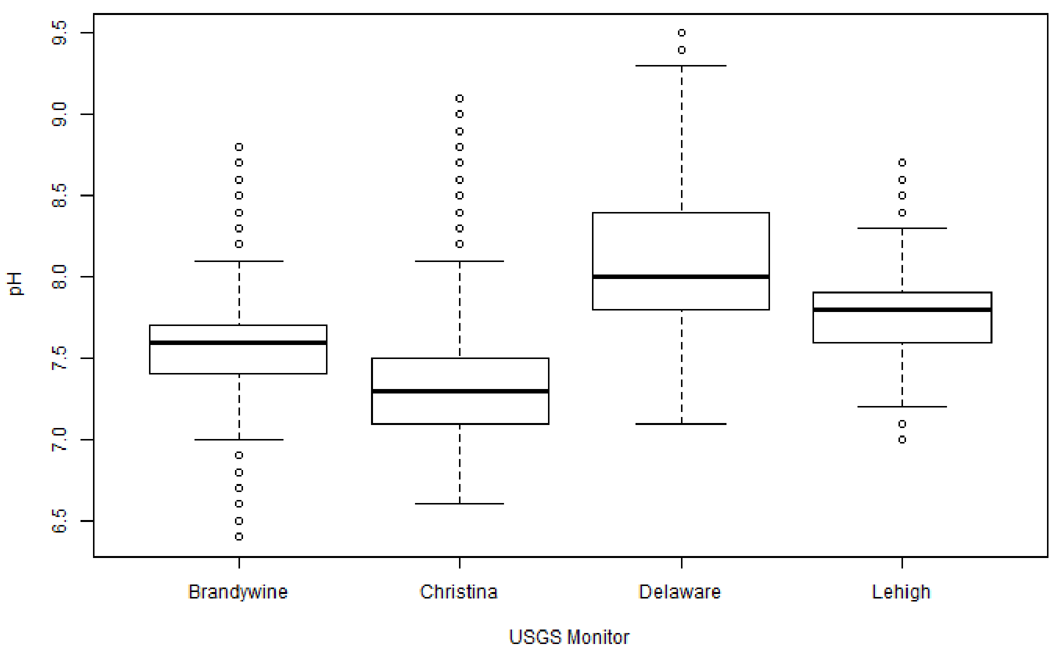

Figure 3.2.7 Summer pH observations at 4 USGS continuous Delaware Basin water quality meters 2011 through 2016.

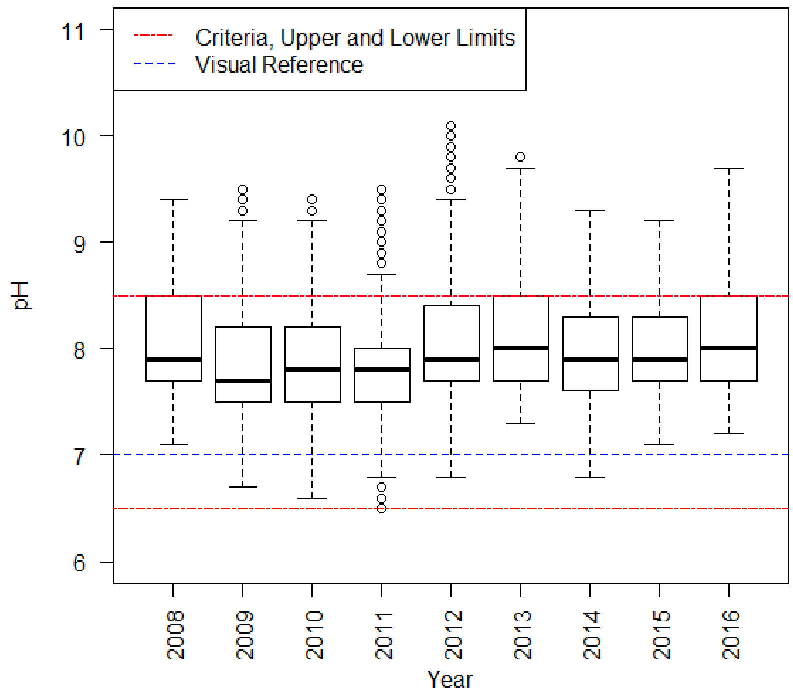

Figure 3.2.8 Instantaneous pH measurements by year, Delaware River at USGS 01463500, Trenton, 2008 through 2016.

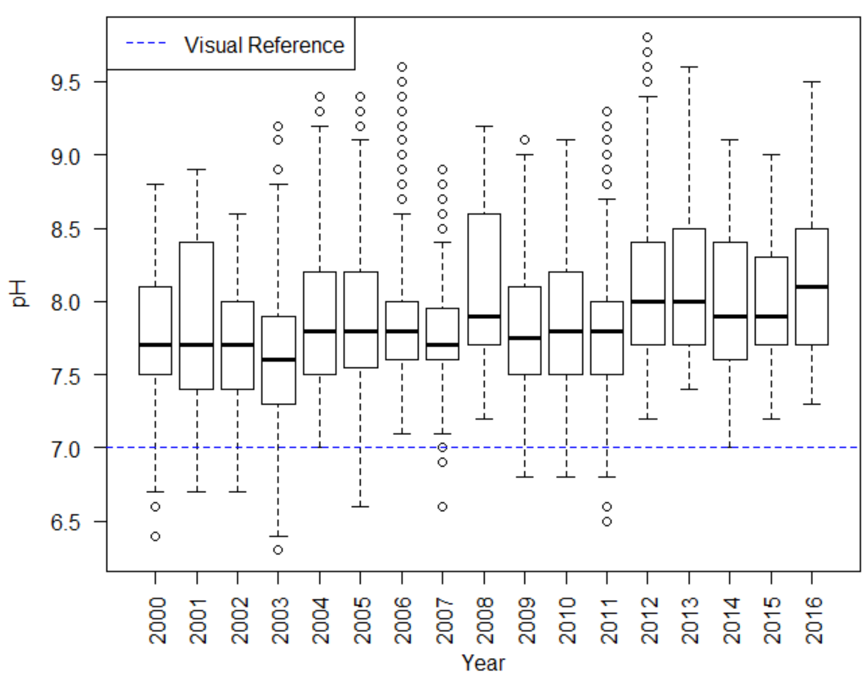

Figure 3.2.9 Daily median pH box and whisker plot at USGS 01463500, Trenton, 2000 through 2016.

3.2.6.5 Actions and Needs

More effort is needed to understand and evaluate routine excursions above a pH value of 8.5 at Trenton. Although this could be a violation of the surface water quality standard, it would be permissible if due to natural conditions. While nutrients may play a role, we have also observed pH excursions above 8.5 in the upper portion of the River, where nutrient concentrations are substantially lower and considered to be oligotrophic.

3.2.6.6 Summary

The pH of surface waters has long been recognized as both a natural and human-induced constraint to the aquatic life of fresh and salt water bodies, both through direct effects of pH and through indirect effects on the solubility, concentration, and ionic state of other important chemicals. Observations of pH at some locations, such as Trenton, show ranges frequently outside of criteria. A portion of this diel swing, however, is attributable to natural primary production.

3.2.7 Temperature

Water temperature is an important factor for the health and survival of native fish and aquatic communities. Temperature can affect embryonic development; juvenile growth; adult migration; competition with non-native species; and the relative risk and severity of disease. Temperature assessment in the non-tidal Delaware River is confounded by artificially lowered temperatures from reservoir releases in the upper portion of the River and the lack of protective ambient criteria.

3.2.7.1 Description of Indicator

Currently, DRBC's criteria for temperature in the non-tidal River is oriented toward point discharge thermal mixing zones. As such, we lack specific temperature thresholds protective of the aquatic communities in the River and its tributaries. Pennsylvania, however, has adopted seasonally specific temperature criteria for warm water fisheries, which will be used for comparison in the upcoming section.

Continuous temperature monitors are deployed at several stations in the non-tidal basin, including the East and West Branches of the Delaware, and the Delaware River at Callicoon, Barryville, and Trenton. Temperature regimes in the non-tidal Delaware are influenced by reservoir operations. Bottom discharges from the Cannonsville and Pepacton Reservoirs release colder water than would naturally occur.

3.2.7.2 Present Status

Figure 3.2.10 shows the summer temperature distributions at four USGS monitors in the mainstem Delaware River at Lordville (river KM 517.6), Callicoon (KM 487.1), above Lackawaxen near Barryville (KM 449.3) and Trenton (KM 216.2), from 2011 through 2016. This plot demonstrates the shift in temperature from the reservoir influenced cold water upstream to warmer temperatures downstream.

To assess whether the temperature regimes observed in the river were protective of aquatic communities, we compared the continuous measurements at Trenton to the Pennsylvania criteria for warm water fisheries. As shown in Figures 3.2.11 below, although the majority of observations are below (meeting) criteria, there are numerous violations, most frequently in the spring.

3.2.7.3 Past Trends

Long term temperature record at Trenton (1954 through 2016) were evaluated to determine if the number of 'violations' would have increased over time (had those criteria been in place). As shown in Figure 3.2.12, no discernable trend in the number of violations per year is evident from the data.

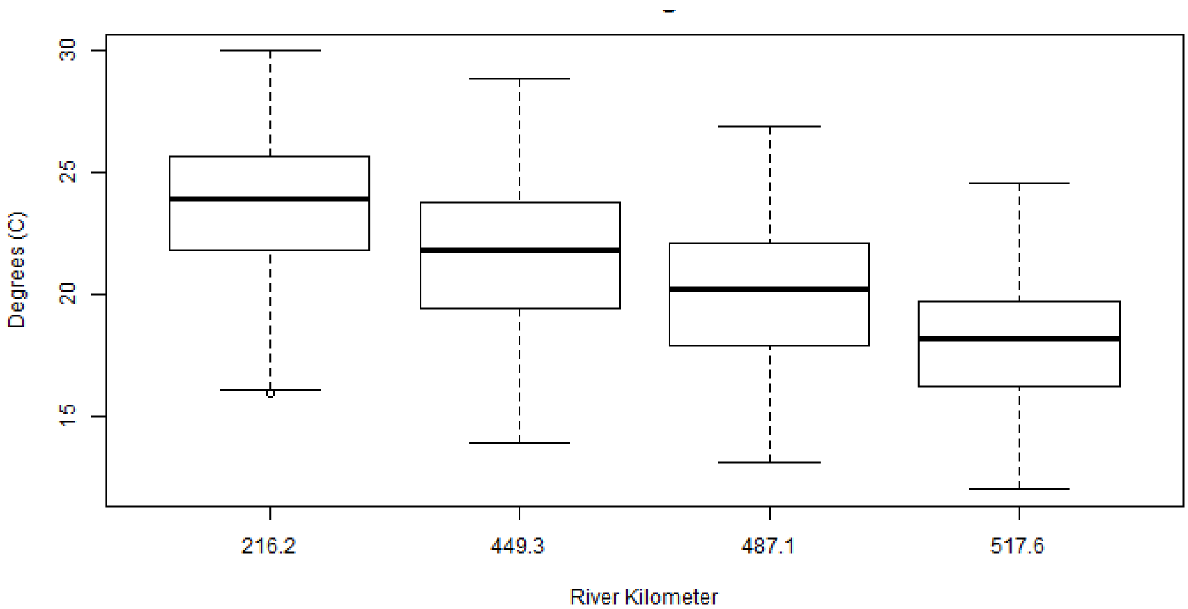

Figure 3.2.10 Summer water temperature box and whisker plot along the main stem of Delaware River, 2011 through 2016.

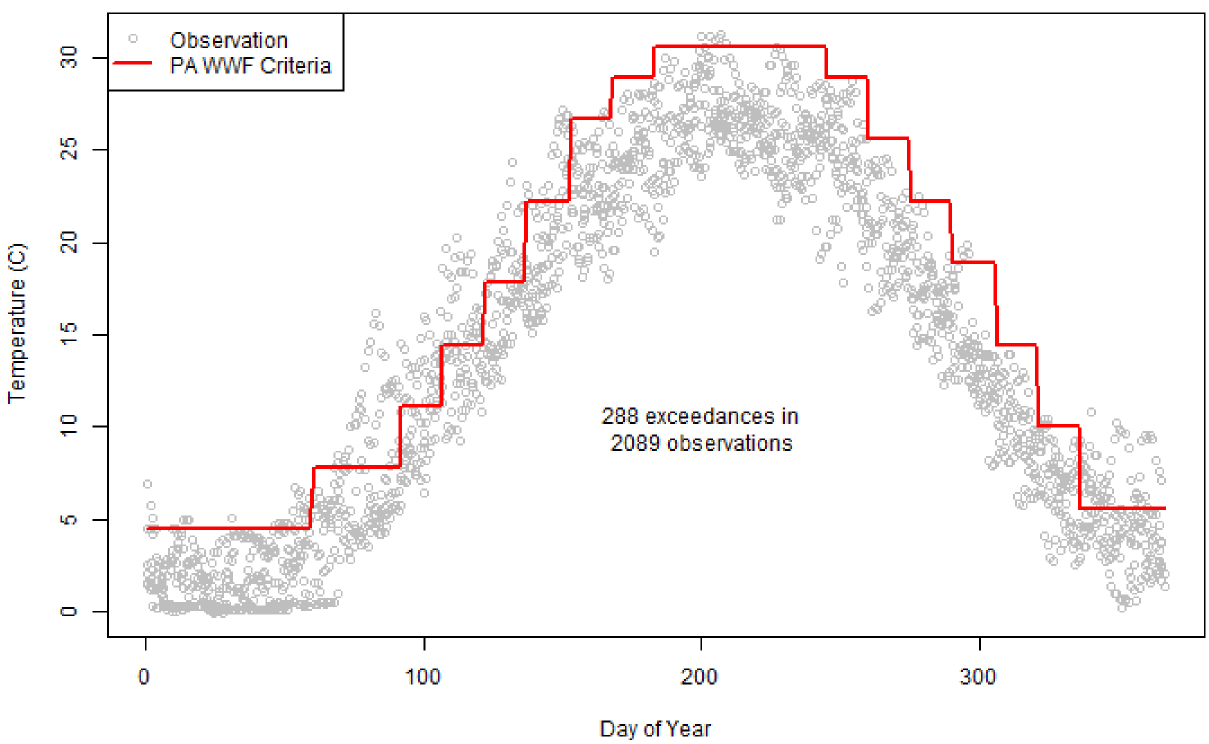

Figure 3.2.11 Comparison of maximum daily water temperature by day of year at USGS 01463500, Trenton to PA Warm Water Fishery Temperature Criteria, 2011 through 2016.

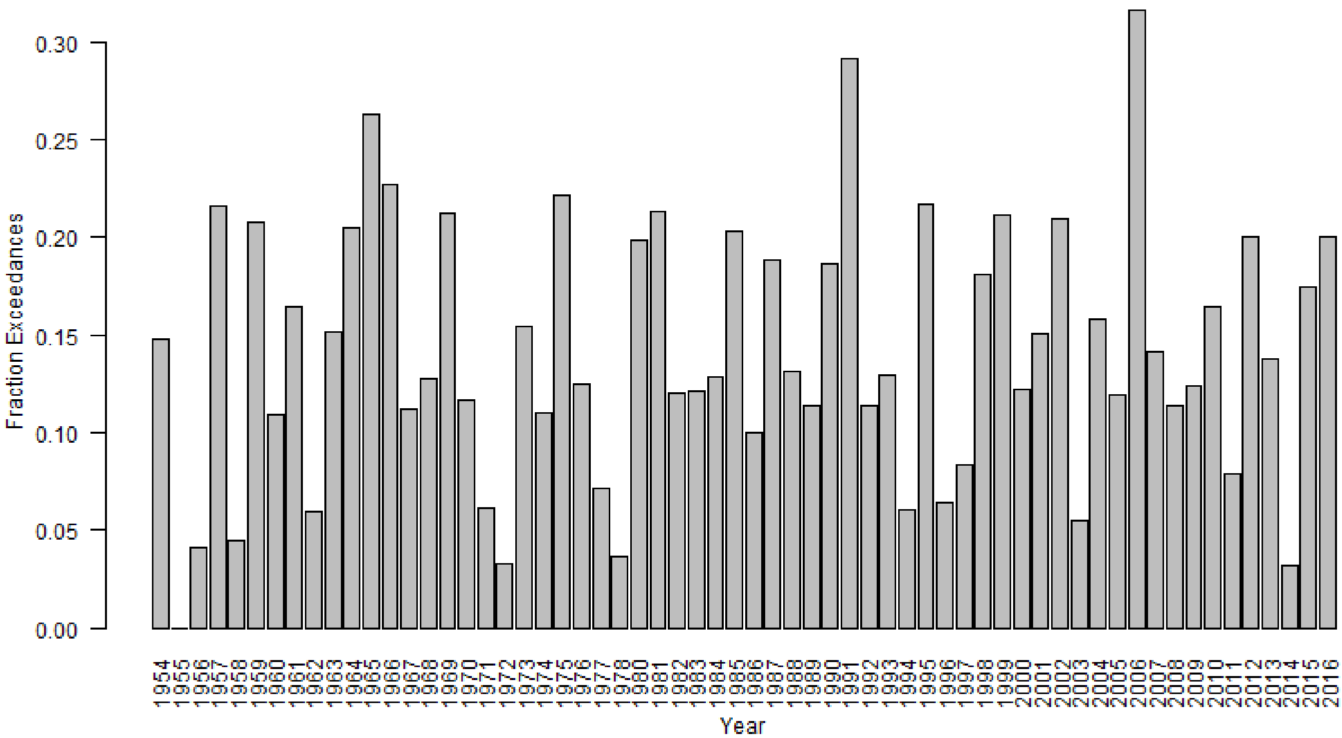

Figure 3.2.12 Water temperature exceedances over PA WWF criteria by year along Delaware River at USGS 01463500, Trenton.

3.2.7.4 Future Predictions

Temperature at Trenton appears to be stable over the continuous monitor period of record. Therefore, temperature at Trenton is expected to remain stable for the foreseeable future. Trenton integrates watershed input from the entire Basin. Individual subwatersheds may see increases associated with development, increased impervious cover, and loss of tree canopy. In addition, global climate change is expected to exert upward pressure on water temperatures.

3.2.7.5 Actions and Needs

The development of temperature criteria in the non-tidal portion of the Delaware River should be continued to protect aquatic communities and allow meaningful interpretation of presently collected data. In addition, stronger linkages between meteorological drivers and resultant water temperatures are needed, so that assessors can distinguish between natural conditions and anthropogenic thermal loads.

3.2.7.6 Summary

Temperature assessment in the non-tidal Delaware River is confounded by artificially lowered temperatures from reservoir releases in the upper portion of the river and the lack of protective ambient criteria.
A comparison the Pennsylvania's warm water criteria shows exceedances at Trenton. The majority of exceedances occur in the spring.

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Suggested Citation for this Chapter

Yagecic, J., R. MacGilivray. 2017. "Chapter 3 - Water Quality" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 97-145.

Data Sources and Processing

Data used in this TREB update comes primarily from USGS continuous monitors, USGS discrete monitoring, and DRBC monitoring programs. Aggregated available data sets were also queried via the National Water Quality Data Portal. Where multiple data sets exist, the authors relied on data for which we had the best first-hand knowledge of quality assurance and quality control.

There are unlimited options available for sub-setting data and presenting it graphically. The authors chose data periods and graphical representations in each instance that conveyed the best understanding of the data.

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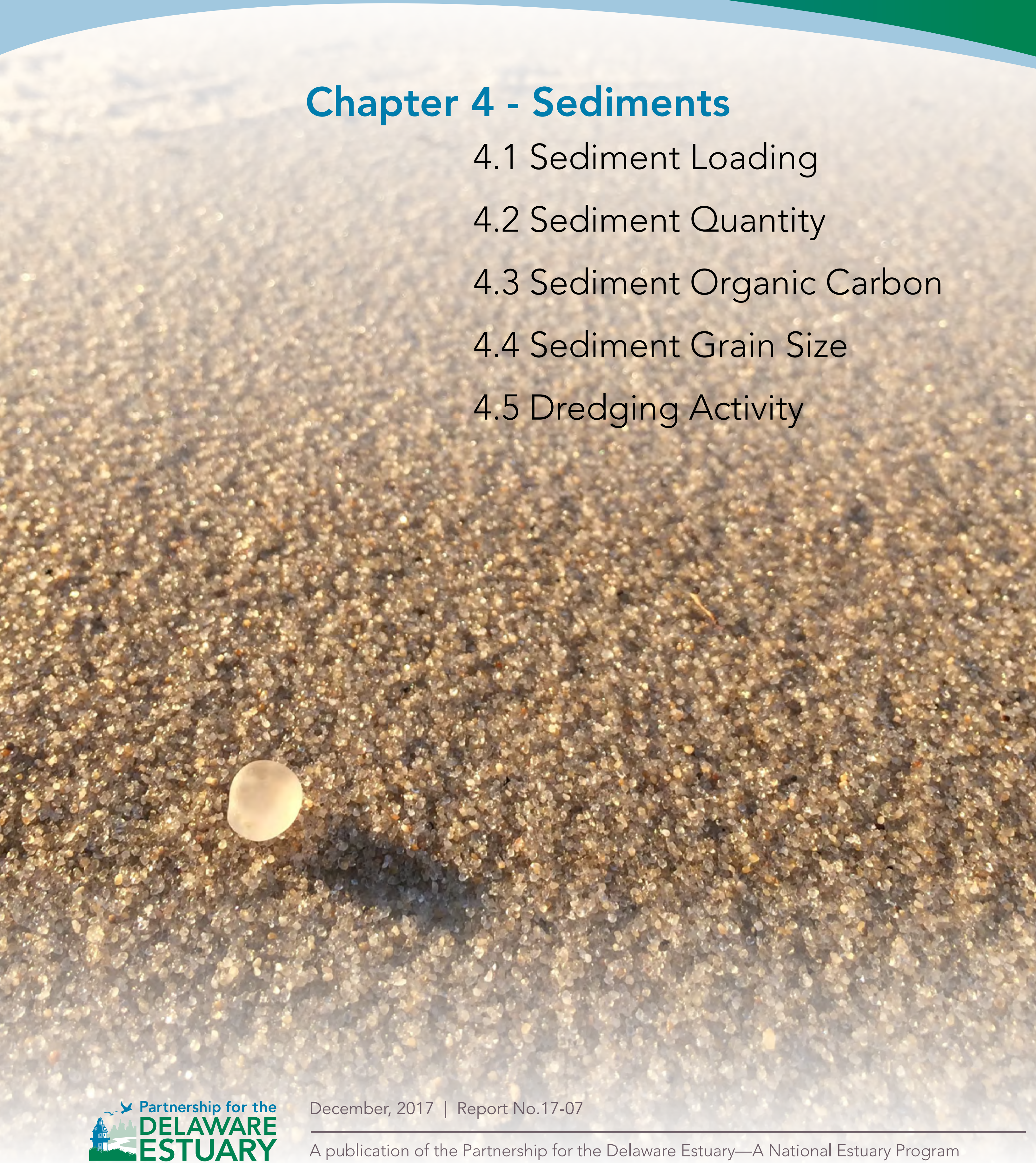

Chapter 4 - Sediments

4.1 Sediment Loading

4.2 Sediment Quantity

4.3 Sediment Organic Carbon

4.4 Sediment Grain Size

4.5 Dredging Activity

Partnership for the DELAWARE ESTUARY

December, 2017 | Report No.17-07

A publication of the Partnership for the Delaware Estuary—A National Estuary Program

4. Sediments

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Reprinted from Partnership for the Delaware Estuary. 2012. Technical Report for the Delaware Estuary and Basin. P. Cole, A. Padeletti, D. Kreeger (eds). PDE Report No. 12-01. 255 pages.

4.1 Sediment Loading

4.1.1 Introduction

Most estuaries of the world, including the Delaware Estuary, are traps for sediment eroded from the watershed above the head of tide. As sea level rose at the end of the last glacial period beginning about 18,000 years ago, the ancestral Delaware River valley was progressively inundated by the sea until the approximate boundaries of the Estuary were established within the past several thousand years (Fletcher et al., 1990). During that period, extensive natural accumulation of both fine- and coarse-grained sediment occurred in the Estuary, creating the three-dimensional geometry and distribution of sediments that existed when Europeans first sailed into the Delaware.

The present state of the Delaware Estuary sediment system represents a highly altered condition compared to what existed as recently as a few centuries ago. In the intervening period, land use changes in the watershed above the head of tide have affected the rate at which new sediment is delivered to the Estuary. Additionally, portions of once natural estuarine shoreline have been modified by construction of bulkheads, seawalls, piers, and wharves to serve the needs of urban and industrial development. Dredged sediment was used as fill to create new land adjacent to the waterway. However, quantitative sediment loading data are available only for the past 60 years.

4.1.2 Description of Indicator

Sediment loading to the Delaware Estuary occurs principally as the Delaware River and its tributaries discharge their suspended load, and a relatively smaller bed load of sediment, at the head of tide. The rate of sediment discharged depends on a number of factors, including antecedent hydrological conditions over the Basin (rainfall and runoff); land use patterns, in particular the degree of disturbed land surface; the number, location, and size of dams on tributaries, which can impound stream sediments above the head of tide; etc. Sediment loading to the Estuary has been monitored quantitatively only for the past six decades. The annual series of suspended sediment discharged to the Estuary from 1950 through 2009 is plotted in Figure 4.1.1. Data are presented for the Delaware River at Trenton (red), the Schuylkill at Philadelphia (green), and the Brandywine at Wilmington (blue), which together represent ~80% of the total freshwater discharged to the Estuary. The graph shows the large annual variability in sediment discharge, indicative of the fact that sediment discharge is highly correlated to freshwater discharge, particularly peak flow events. The drought period of the mid-1960s has relatively low sediment discharge, whereas the period from 2004 through 2006, with several large flood events in the region, shows higher sediment discharge.

4.1.3 Present Status

The mean annual sediment discharge over the past six decades at these three locations is 1.26 million metric tons. Together the three gaged locations represent 80% of the drainage area to the Delaware Estuary. It is assumed here that the remaining 20% of the Estuary drainage area not gaged for sediment discharge contributes sediment at the same rate as the gaged 80% of the drainage basin. Consequently, the mean annual sediment discharge to the Estuary from the entire Basin is estimated as 1.58 million metric tons (1.6 million rounded). For historical perspective, Mansue and Commings (1974) analyzed suspended sediment input to the Delaware Estuary and their data show an average annual input from the Delaware, Schuylkill, and Brandywine Rivers of 1.0 million metric tons per year, with a total suspended solids input to the Estuary from all sources estimated as 1.3 million metric tons annually. The sediment discharge data in Figure 4.1.1 suggest no apparent trend of increase or decrease in sediment discharge over the period of record.

4.1.4 Past Trends

There is no apparent temporal trend for increased or decreased suspended sediment loading to the Estuary over the past six decades.

4.1.5 Future Predictions

It is reasonable to expect that the next decade to several decades will resemble the past six decades in terms of sediment loading. During high-flow events in the watershed, larger quantities of suspended sediment stored in and along streams will be flushed to the Estuary, and the sediment load will be small in years with low inflow regimes.

4.1.6 Actions and Needs

Continued monitoring of suspended sediment discharge at the presently gauged locations is recommended.

4.1.7 Summary

The mean annual contribution of new sediment to the Delaware Estuary from the watershed above the head of tide has averaged 1.6 million tons per year over the past six decades. However, the seasonal and year-to-year variability in sediment discharge is large and reflects the underlying natural variability of the hydrologic regime of the Delaware watershed. There is no apparent trend in this record indicating either a long-term increase or decrease in sediment loading to the Estuary from the watershed above the head of tide.

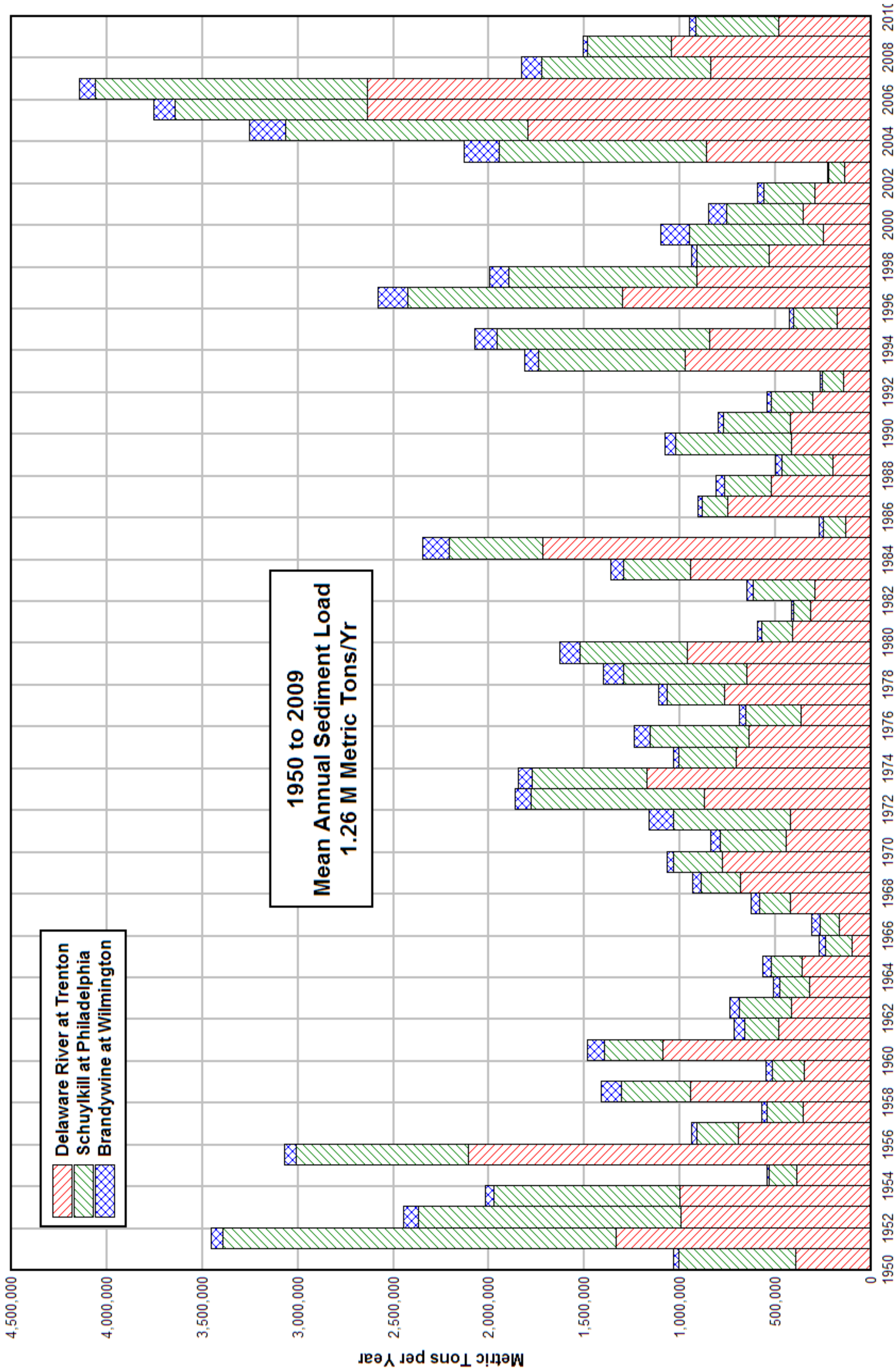

Figure 4.1.1 Delaware Estuary Sediment Load Time Series 1950 through 2009.

4.2 Sediment Quantity

4.2.1 Description of Indicator

The most useful indicator of sediment quantity in an estuary is a spatially complete sediment budget that identifies the principal sources, sinks, pathways, and processes involved in sediment transport and distribution. In an ideal budget, all sediment sources and sinks are identified and quantified, and all processes that add, transport, and remove sediment are also identified and quantified. However, sediment transport processes are highly variable in time and space, and quantifying source and sink terms always involves a level of temporal and spatial averaging. Since an estuary may exhibit long-term net accumulation of sediment, or long-term net loss, it is not necessarily expected that the system is at steady state and that the source and sink terms will balance to zero.

Table 4.2.1 1946-1984 Estuary Sediment Mass Balance. Quantities in millions of metric tons per year (Walsh, 2004).

Sources		Sinks	
Bottom Erosion	3.4	Maintenance Dredging	2.8
Upland Fluvial Input	1.3	Marsh Accumulation	2.6
TOTAL SOURCES	4.7	TOTAL SINKS	5.4

4.2.2 Present Status

The most recently published quantitative sediment budget for the Delaware Estuary was presented in "Anthropogenic Influences on the Morphology of the Tidal Delaware River and Estuary: 1877 – 1987" (Walsh, 2004). The sediment budget data from this report is presented in Table 4.2.1.

Table 4.2.1 illustrates a number of salient points. First, although the source and sink term do not balance in an absolute sense, they are sufficiently close given the uncertainty of the calculations and measurements involved that they balance to a first order of accuracy. In the list of sources it can be seen that the largest category is "bottom erosion." This indicates that for the period and areas included in the analysis, scour of the bed of the Estuary was observed to be the largest source of sediment available to the system, larger by a factor of 2.6 than the average annual input of "new" sediment from the watershed above the head of tide. In the list of sinks, the largest contributor is dredging, followed by sediment accumulation in marshes. This implies that despite the large lateral retreat of fringing marshes of Delaware Bay documented over the past 160 years, tidal marshes may accumulate as much sediment mass vertically than they lose to lateral retreat (Table 4.2.1).

Although Table 4.2.1 represents the latest published sediment budget for the Delaware Estuary, U. S. Army Corps of Engineers (USACE) Philadelphia District has been working with Woods Hole Group (Falmouth, MA) and Dr. Christopher Sommerfield of the University of Delaware to update this budget. Preliminary findings of the sediment budget reevaluation that differ from Walsh (2004) include the following:

- Suspended sediment loading ("Upland fluvial input"): 1.6 M metric tons/year
- Inorganic sediment accumulation in tidal marshes: 1.1 M metric tons/year

Additional items related to this updated sediment budget that are being examined by the Woods Hole Group and Dr. Sommerfield include:

- Suspended sediment inventory in the Estuary based on University of Delaware oceanographic surveys

- ○ Analysis of maintenance dredging records provided by USACE
- ○ Bottom sedimentological data (grain size and bulk density)
- ○ Digital shoreline datasets – analyzed for shoreline change for periods of interest
- ○ Digital bathymetric datasets - analyzed for bathymetric change over several periods

4.2.3 Past Trends
Previous investigators have compiled sediment budgets for the Delaware Estuary, including Oostdam (1971) and Wicker (1973). However, given the variety of data sources and analytical approaches applied in historic sediment budget research, it is not apparent that a meaningful historic trend can be derived from comparison of budgets created by different researchers at different times. However, the in-progress work by Woods Hole Group and Dr. Christopher Sommerfield, which applies a consistent methodology to several periods from 1890 to the present, will allow a meaningful comparison of Estuary sediment budgets over time to identify historic and presumably future trends.

4.2.4 Future Predictions
[See above]

4.2.5 Actions and Needs
Sediment budget research in the Delaware Estuary has evolved substantially in the past decade in terms of sources of historic data, analytical approaches to the subject, and also instrumentation to directly measure relevant hydrodynamic and sediment transport parameters. Continued efforts to improve our understanding of sediment transport phenomena and the Estuary sediment budget in general are recommended.

4.2.6 Summary
Sediment quantity is an indicator that is best represented by an estuary sediment budget. The latest published sediment budget for the Delaware Estuary indicates that the bed of the Estuary has eroded at a rate that exceeds the average annual rate at which new sediment is supplied from the watershed, and that maintenance dredging is the principal mechanism by which sediment is "permanently" removed from the Estuary. Ongoing research should allow a significant quantitative improvement in identifying the processes and terms of the sediment budget.

4.3 Sediment Organic Carbon

4.3.1 Description of Indicator

Sediment total organic carbon (TOC) is the sum amount of organic carbon that is bound to organic material. Organic carbon is both natural and anthropogenic in origin. Natural sources include leaf litter, plant, and animal waste. Examples of anthropogenic sources of organic carbon include pesticides, and municipal and industrial wastewater. It has an affinity for fine-grained sediment particles and its concentrations typically correlate with the percentage of silt and clay in the sediment.

Studies have indicated that the initial increase in organic carbon provides food to the benthos. Too much organic carbon can create an environment where opportunistic species dominate the area. If this occurs over a substantial amount of time, evidence suggests that bacterial mats will dominate the area. Elevated concentrations of TOC commonly suggest greater potential of contaminants to accumulate and impact the aquatic food web. Although the Delaware does not exhibit the typical signs of eutrophication (e.g. fish kills, algal blooms, etc) TOC remains a useful indicator of contamination by organic pollutants.

4.3.2 Present Status

There are data sets that indicate concentrations of TOC are the lowest they have been in decades in the Delaware Estuary. In particular, the Delaware River Watershed Source Water Protection Plan contains TOC data from 1993 – 2006. Slight fluctuations from year to year were noted, especially in the maximum value of TOC detected, but the mean and median values indicated an overall decline in TOC concentrations in mg/L over the course of the last 13 years.

In addition, Chapter 3 of the 2007 USEPA National Estuary Coastal Condition Report indicates that the Delaware Estuary was rated as "good" for sediment TOC. Sixty-seven percent of the estuarine area was rated "good" for this component, with 19% rated "fair". No portions of the Delaware were rated "poor" although data were unavailable for 14% of the Estuary.

The spatial distribution of TOC as measured in sediment samples obtained in 2008 as part of the Delaware Estuary Program DEBI (Delaware Estuary Benthic Inventory) effort is included as Figure 4.3.1.

4.3.3 Past Trends

Past trends indicate that TOC was present in greater concentrations in the Delaware Estuary than current conditions. The system is typically turbid, and the greater the TSS, the greater the chance of having elevated TOC concentrations, especially when the sediment entering the Delaware Estuary was silty in origin.

4.3.4 Future Predictions

Continued improvements in wastewater treatment, storm-water management and smarter land use planning are projected to reduce the amount of TOC delivered to the Delaware Estuary.

4.3.5 Actions and Needs

It is stated in the 2007 National Estuary Program Coastal Condition Report that the "regional NEP programs have found that the problems associated with eutrophication are dwarfed by problems from other water quality stressors". This does not mean that eutrophication is not a problem in the Delaware Estuary. It just implies that greater concerns, such as industrial inputs to the system (PCBs) are a bigger issue at this time. There are still areas of the Delaware Estuary with levels of dissolved oxygen less than 5mg/L.

Although the hydromorphic features of the Delaware are favorable in terms of creating a well mixed system, low DO levels, along with levels of nitrogen and chlorophyll a comparable to the Chesapeake Bay system insinuate that additional data regarding TOC should be collected to better understand the system.

4.3.6 Summary

TOC levels have declined in recent decades with improved waste- and storm-water management.

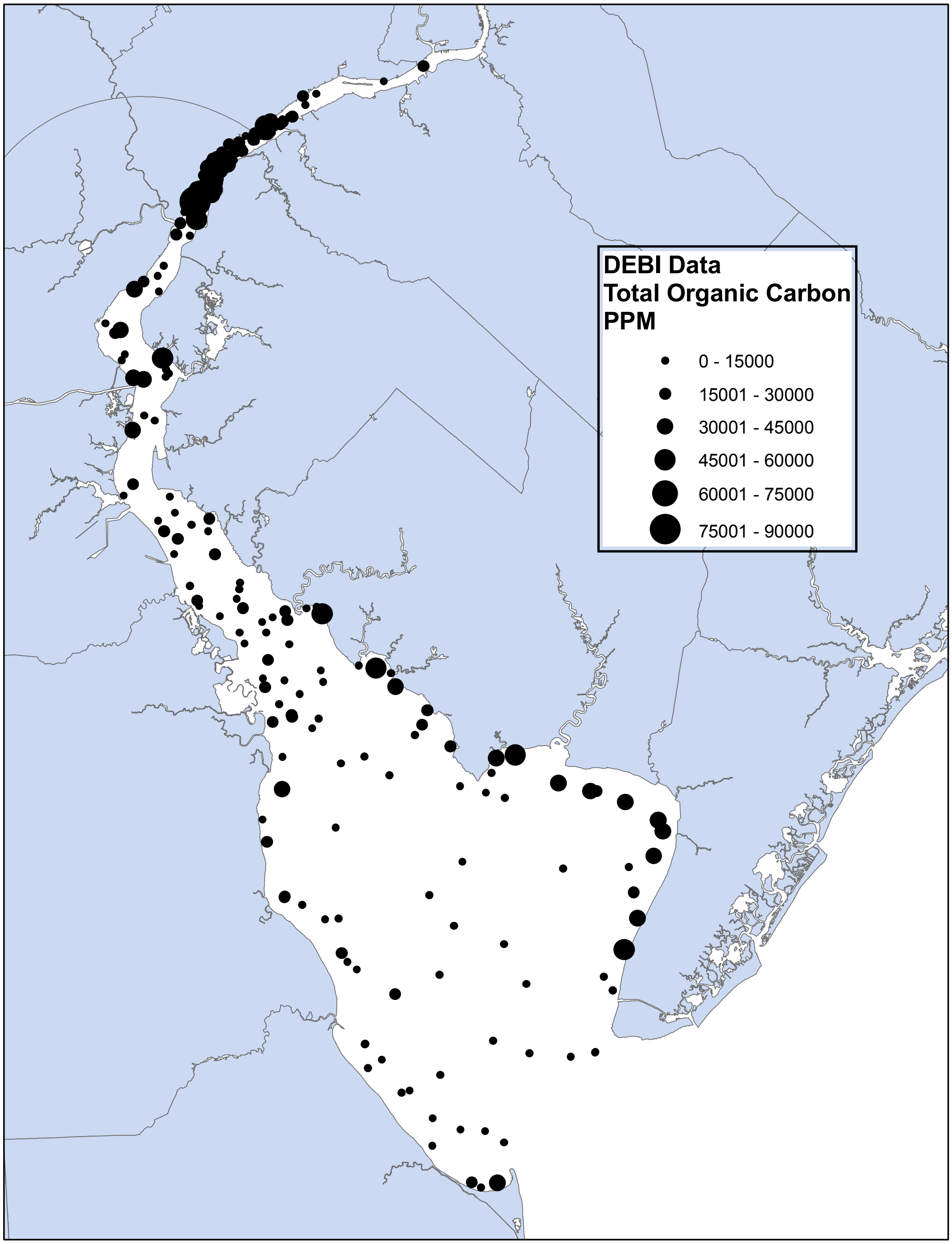

Figure 4.3.1 Total organic carbon concentrations in 2008 DEBI sediment samples.

4.4 Sediment Grain Size

4.4.1 Description of Indicator

Sediment grain size is an ecological indicator only to the extent that benthic organisms show preferences for, and thus inhabit, specific types of bottoms. Grain size, carbon (food) content, and frequency of bed disturbance explain most of the spatial variation in organism type and activity.

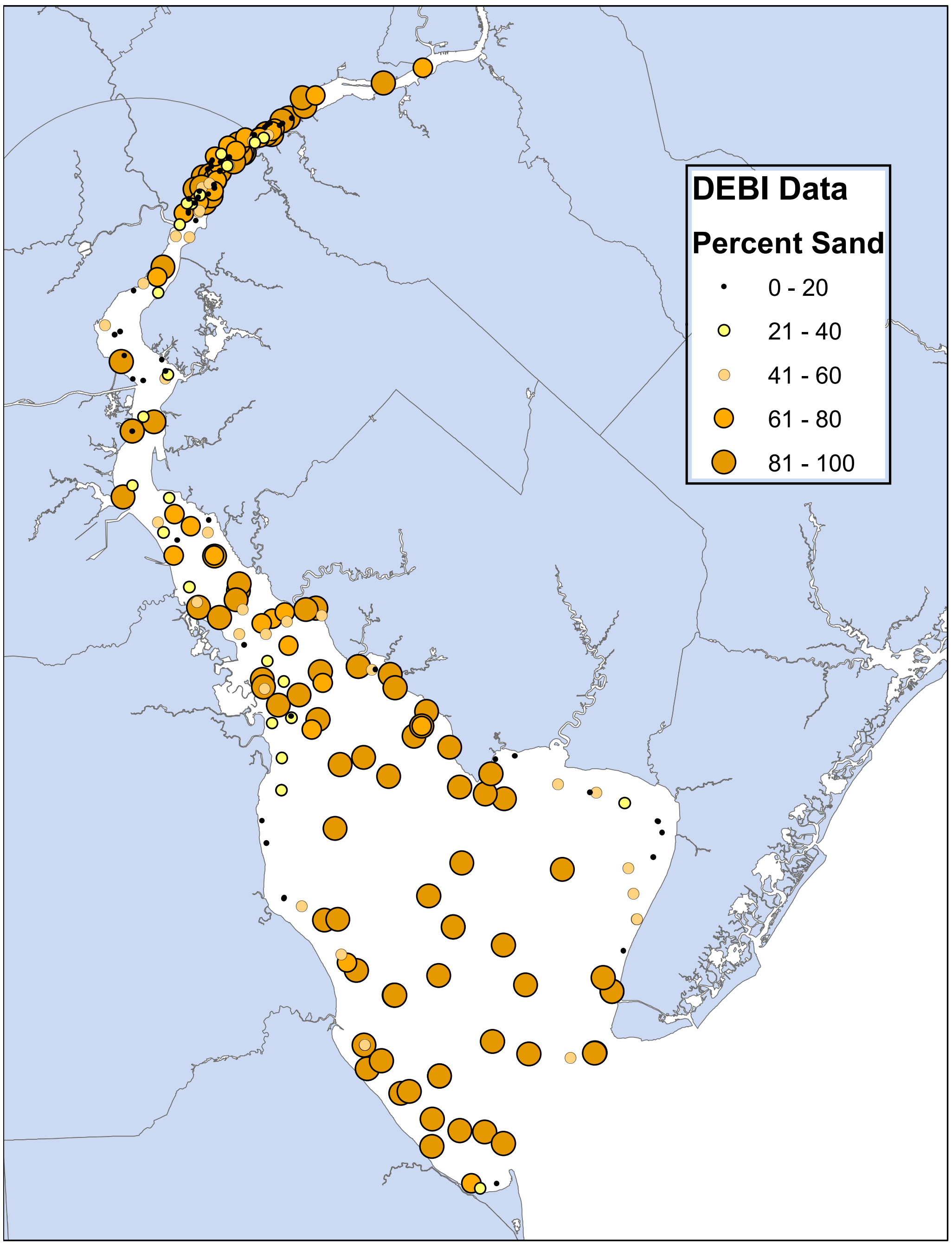

Figure 4.4.1 Percent sand in 2008 DEBI sediment samples.

4.4.2 Present Status

The present spatial distributions of sand and silt-clay content are presented in Figures 4.4.2 and 4.4.3, respectively. The sediment grain size samples were obtained in 2008 as part of the Delaware Estuary Program DEBI (Delaware Estuary Benthic Inventory) effort. The two plots indicate the inverse relationship between sand and silt-clay ("mud") fractions sediments in the Delaware Estuary. The plots also indicate the heterogeneity of sediment types and patchy distribution at many locations within the Estuary, particularly in the reach from Wilmington to Liston Point. In this segment of the Estuary, the dominant bottom sediment type is mud whereas downstream of Liston Point, the bottom is dominated by mixtures of sand and gravel with lesser amounts of mud. The zone of dominant muddy bottom corresponds to the "estuary turbidity

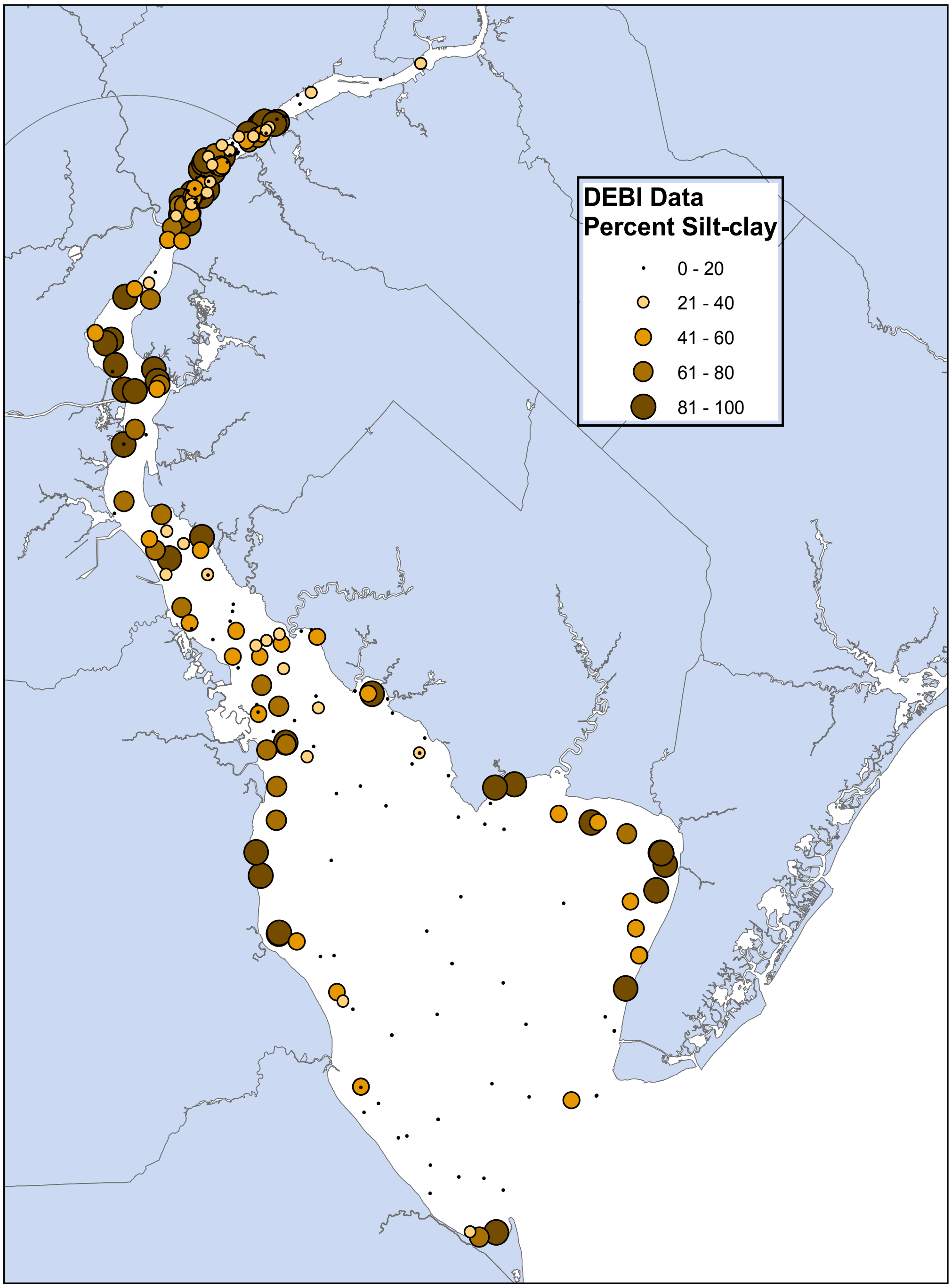

Figure 4.4.2 Percent silt-clay in 2008 DEBI sediment samples.

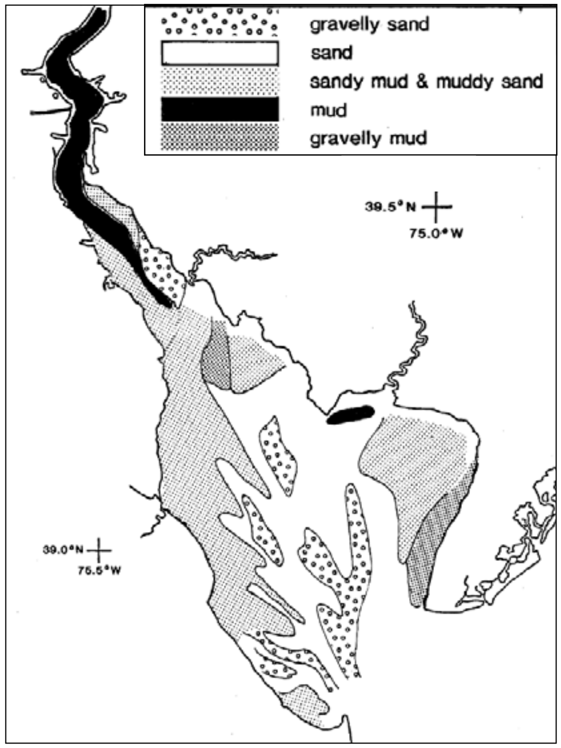

Figure 4.4.3 Bottom sediments as from Biggs and Church (1984).

maximum" (ETM), which results from the complex interaction of freshwater inflows from upstream sources with denser, more saline water from the Atlantic Ocean.

4.4.3 Past Trends

Although sufficient data do not exist to assess the degree to which sediment grain size distribution may have changed over time, the 2008 DEBI data are broadly comparable to the bottom sediment distribution that is depicted in Biggs and Church (1984), Figure 4.4.1.

4.4.4 Future Predictions

Although it is plausible to predict that sediment best management practices (BMPs) in the watershed will at some point lead to reductions in suspended sediment supply to the Estuary, there is no evidence (Fig 4.1.1) of this reduction having occurred over the past six decades. It is therefore probable that there will be no significant changes in sediment grain size distribution in the Estuary within the next few decades.

4.4.5 Actions and Needs

Sediment grain size data should continue to be collected and archived as a part of future research on benthic organisms. It is suggested this be conducted concurrent with other benthic research.

4.4.6 Summary

Sediment grain size is not intrinsically an indicator of estuary health. There are organisms and ecological communities that productively inhabit the full range of bottom sediment classes that exist in the Estuary. Although fine-grained sediment can potentially have higher concentrations of adsorbed pollutants than sand and gravel, fine grained sediment bottom is a natural component of all estuaries and can support a range of natural benthic communities.

4.5 Dredging Activity

4.5.1 Description of Indicator

The earliest navigation improvements within the Delaware Estuary that involved dredging began in 1890 in order to meet the growing needs of waterborne commerce in the region. The USACE has been the principal agency responsible for the construction and subsequent maintenance dredging of Federal navigation projects authorized by Congress. The first project was the construction of a 7.9 meter (26 ft) deep channel from Philadelphia to naturally deep water in the bay. Between 1890 and 1942, the Delaware River, from Philadelphia to the Sea channel, was incrementally deepened to 9.1 meters (30 ft), 11.0 meters (36 ft), and finally to the existing channel depth of 12.2 meters (40 ft). Congress authorized the deepening of this channel to 13.7 meters (45 ft) in 1992, and a portion of that work was initiated in 2011. Each successive channel deepening has created a quantity of "new work" dredging. Following completion of dredging to a specified depth, "maintenance" dredging is performed periodically to remove shoaled sediment from the channel in the interest of navigational safety and efficiency. Other deep-draft navigation projects in the Estuary include: Delaware River, Philadelphia to Trenton; Wilmington Harbor, Christina River, DE; and Schuylkill River, Philadelphia, PA. The Delaware River, Philadelphia to Sea channel is the longest and deepest of all navigation channels in the Estuary, and correspondingly has required the largest dredging effort, approximately 72% by volume, of all Delaware Estuary dredging over the past decade.

4.5.2 Present Status

The cumulative maintenance dredging from all federal navigation projects in the Delaware Estuary for the period 1997 through 2009 is presented in Figure 4.5.1, which illustrates the relative portion of Delaware Estuary dredging associated with each project. The average annual total of all Delaware Estuary dredging in this period is 2.6 million cubic meters (3.35 million cubic yards) per year. Channel shoaling, and hence channel dredging, is a highly localized phenomenon. There are four high shoaling-rate locations in the

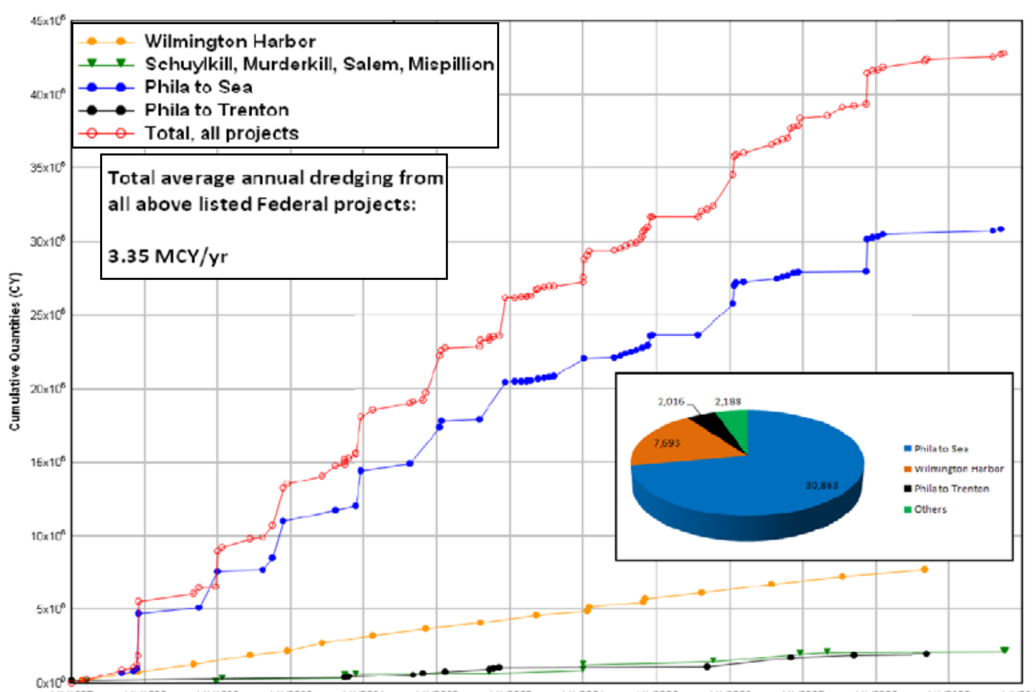

Figure 4.5.1 Cumulative maintenance dredging summary from federal navigation projects in Delaware Estuary, 1997-2009.

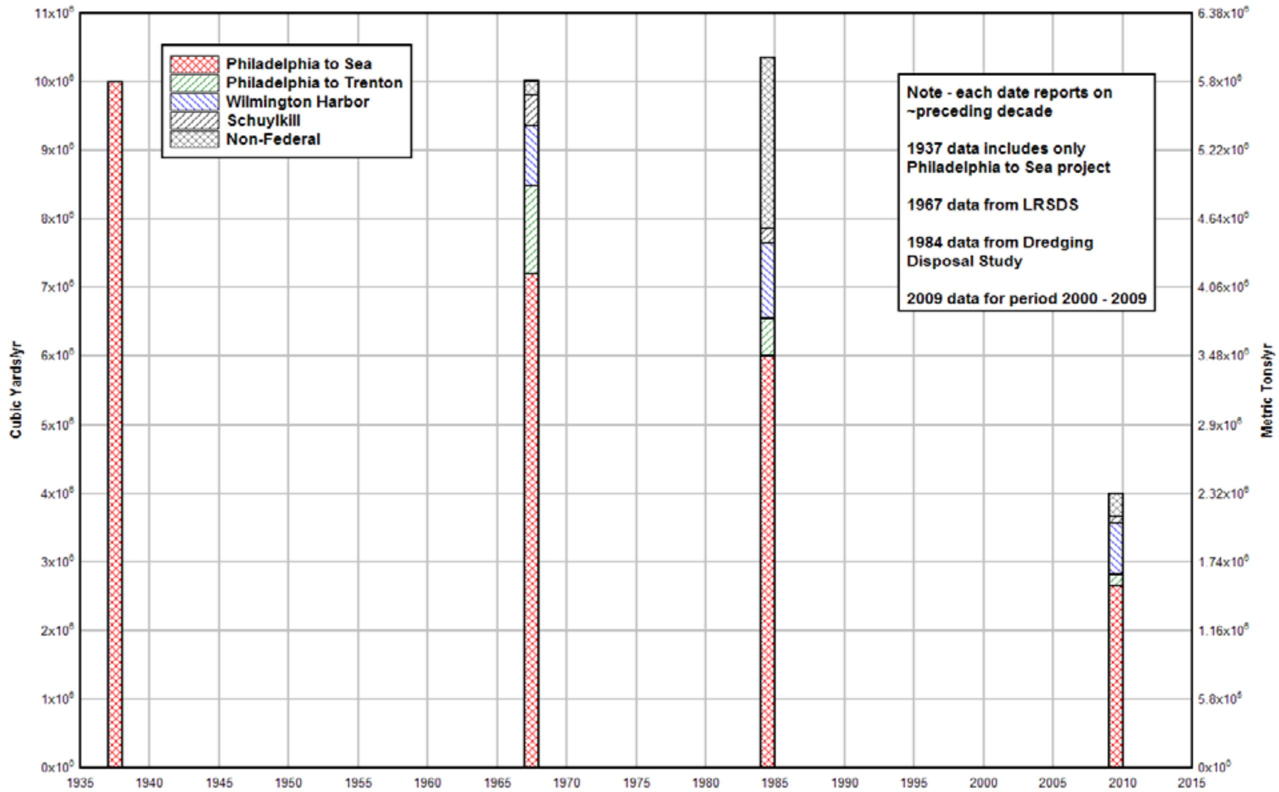

Figure 4.5.2 Average annual maintenance dredging rates within the Delaware Estuary in 1937, 1967, 1984, and 2009.

Estuary within a 30 km reach between the Chesapeake and Delaware (C&D) Canal and Marcus Hook (including the Wilmington Harbor project) that together necessitate about 80% of all maintenance dredging within the entire Estuary. Note that since 1955, essentially all sediment dredged from the estuarine system has been placed in upland dredged material disposal sites.

4.5.3 Past Trends

Maintenance dredging quantities have been compiled in a number of USACE reports. A 1937 USACE report states "maintenance dredging amounting to about ten million cubic yards annually" was required over the preceding 25 years. Subsequent USACE reports (USACE 1967, USACE 1984) also present estimated annual navigation project dredging in the Estuary. Figure 4.5.2 presents the annual dredging rates from these four dates (1937, 1967, 1984, and 2009). Where data were reported for projects in addition to the Philadelphia to Sea channel, these are included in Figure 4.5.2. The quantities are displayed in terms of cubic yards per year on the left axis and are converted to their corresponding sediment mass values of "metric tons per year" (right axis) using the relationship of 753 kg/m^3 (Walsh 2004). The quantities display the trend of reduced maintenance dredging over the past several decades.

4.5.4 Future Predictions

The deepening of the Delaware River Main Channel from 12.2 meters (40 ft) to 13.7 meters (45 ft) is expected to lead to approximately a 20% increase in annual maintenance dredging.

4.5.5 Actions and Needs

Continued monitoring and reporting of maintenance dredging quantities is a routine function of USACE. It is recommended that future work on all aspects of the Delaware Estuary sediment management and sediment budget include regular coordination with USACE regarding dredging quantities.

The Regional Sediment Management Implementation Workgroup (RSMIW) continues to serve as a platform for the system-wide approach to expand beneficial use of dredged material in the Delaware River Basin. Through quarterly meetings, regional stakeholders convene to discuss site-specific challenges, streamline regulatory processes, cultivate programmatic linkages and share information to better understand sediment dynamics and quality. The RSMIW tracks the progress of regional projects and have selected Recommended Actions, per the RSM Plan, to continue to move forward on the goals of the workgroup. RSMIW aims to better align future dredging opportunities with ecosystem needs that are both economically feasible and scientifically sound with the aid of the best available technology and spatial tools.

4.5.6 Summary

Dredging activity is not a conventional ecological indicator. It is a direct measure of the degree to which sediment shoals within navigation projects and must be removed in the interest of safe and efficient navigation. The historic trend over the past five decades has been for diminished average annual dredging quantities, but the cause of this decline has not been rigorously investigated to date.

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Suggested Citation for this Chapter

Gebert, J. A., R. Searfoss. 2012. “Chapter 4 - Sediments” in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 147-159.

Further Reading

For more information about sediments in the Delaware Estuary, please see the Delaware Estuary Regional Sediment Management Plan: http://www.state.nj.us/drbc/library/documents/RSMPaug2013final-report.pdf

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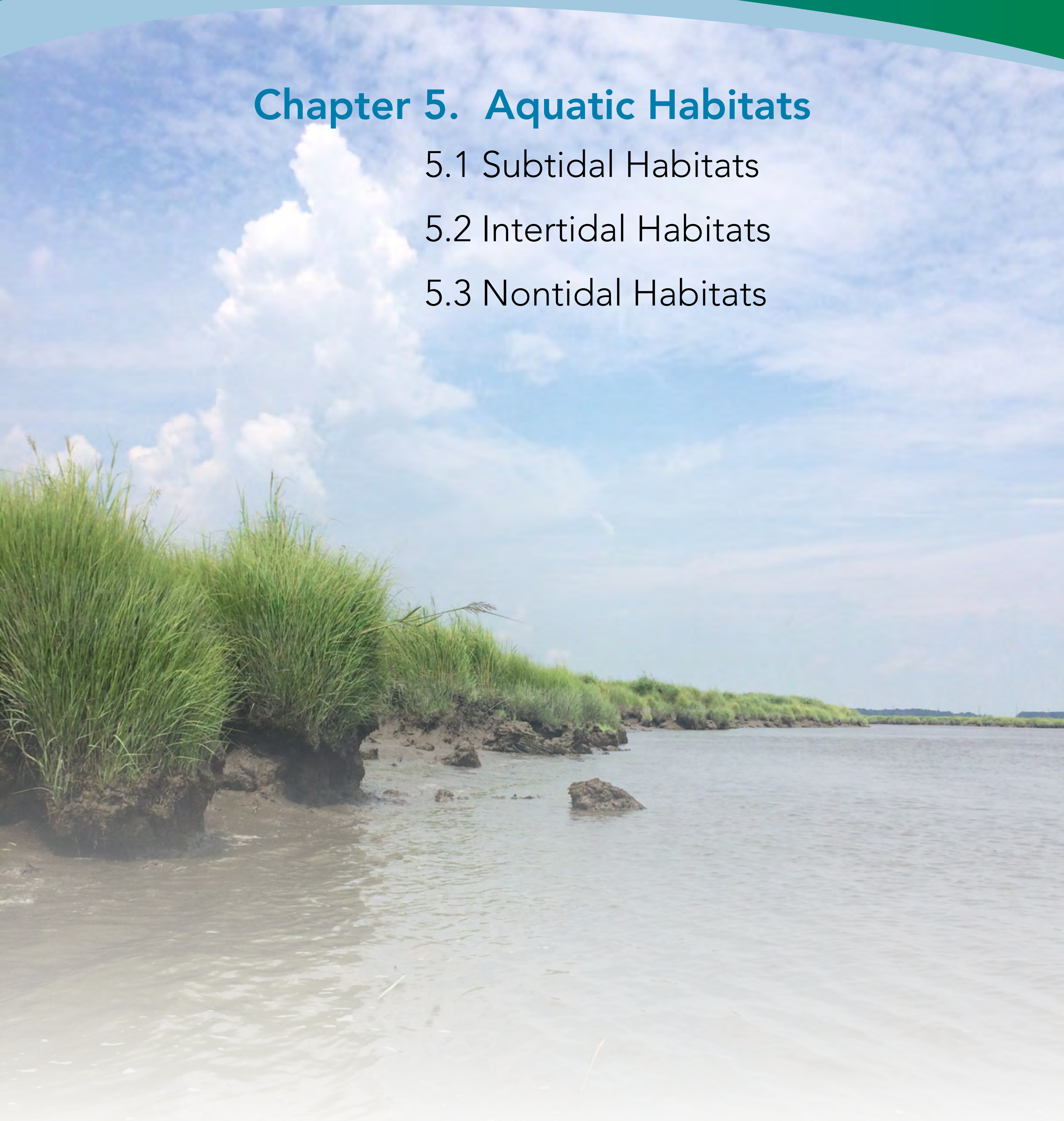
Chapter 5. Aquatic Habitats



Partnership for the DELAWARE ESTUARY

December, 2017 | Report No.17-07

A publication of the Partnership for the Delaware Estuary—A National Estuary Program

5. Aquatic Habitats

5.1 Subtidal Habitats

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Reprinted from Partnership for the Delaware Estuary. 2012. Technical Report for the Delaware Estuary and Basin. P. Cole, A. Padeletti, D. Kreeger (eds). PDE Report No. 12-01. 255 pages.

5.1.1 Introduction

While surveys of the benthos have occurred in the Delaware Bay and River since the 1950s (Table 5.1.1) the recent Delaware Estuary Benthic Inventory (DEBI) is the most comprehensive and intensive study ever conducted (Fig 5.1.1). Due to the extent of the data produced in the DEBI project, it is the focus, though not exclusively, of this indicator.

The DEBI project was led by The Partnership for the Delaware Estuary, one of twenty-eight National Estuary Programs. In 2005, The Partnership for the Delaware Estuary recognized a fundamental need for a benthic ecosystem assessment that would inventory the physical and biological conditions of the bottom of the open water tidal system of the Delaware River and Bay. This priority need was articulated in early 2005 when the Partnership convened a science and management conference that brought together more than 250 scientists, managers and science-interested people to summarize the current state of science and to identify and prioritize science and management needs for the Estuary. Consensus views from the conference were summarized in the "White Paper on the Status and Needs of Science in the Delaware Estuary" (Kreeger, et al. 2006) that called for a better understanding of benthic conditions.

Soon after the white paper, The Partnership and its collaborators around the estuary designed the Delaware Estuary Benthic Inventory (DEBI) program to fill the vital data gap in our understanding of the estuary's ecosystem by characterizing bottom dwelling biological communities. By adding a more spatially comprehensive biological layer to existing maps of physical bottom conditions and historical surveys of benthic communities, findings from DEBI are expected to aid scientists, coastal managers, stakeholders, and decision-makers interested in trophic relationships, fisheries, pollutant distributions, water quality, and other

Figure 5.1.1 Pictures from sampling during the 2009 Delaware Estuary Benthic Inventory (DEBI). Photo credit: Partnership for the Delaware Estuary.

Table 5.1.1 Summary of benthic Surveys in the Delaware River and Estuary conducted 1951-2008 in DEBI final report.

Metadata	Amos DRIC	Maurer et al.	EMAP	NOAA S&T	MAIA	NCA	DEBI	Comments
Year(s) and Seasonality	1950's, mostly summer	1972-73, summers	1990-1993, summers	1997, September	1997-98, summers	2000-2006, summers	2008, summers	Summertime for peak abundances, most favorable weather
Spatial Domain	Delaware River and Estuary	Delaware Bay	Delaware Bay	Delaware River and Bay and coastal Atlantic	Delaware River (to Trenton) and Bay	Northeast U.S., Delaware Bay to Maine	Delaware River and Bay	
Number of Stations	Estimated to be about 130	207	25	81	88	138	230	Remarkably, almost 900 stations over all 7 surveys
Sampling Design	Various, piggybacked on hydrographic and zooplankton projects	Lines running along channels, bathymetry	Probabilistic	Probabilistic with strata	Probabilistic	Probabilistic with strata	Probabilistic with salinity and sediment strata	
Sampling Gear	Grabs, dredges, buoy scrapings, plankton tows	0.1 m2 Petersen grab and 1.0-mm mesh	EMAP grabs and water quality, 0.5-mm mesh sieve	Young modified Van Veen, 0.5-mm mesh sieve	0.04-m2 Young-modified Van Veen grab sampler, 0.5-mm mesh screen	0.04 m2 Young-modified Van Veen, 0.5-mm mesh sieve	0.04 m2 Young-modified Van Veen, 0.5-mm mesh sieve	Note differences in sampling gear and sieve mesh sizes
Additional Data	Hydrographic	Hydrographic and sediment	Hydro-graphic, sediment and stressors	Hydrographic, sediment and stressors	Hydrographic, sediment and stressors	Hydro-graphic, sediment and stressors	Hydrographic, sediment and stressors	Hydrographic: temperature and salinity; sediment: grain size or % sand, % silt-clay; stressors: DO, heavy metals, organic pollutants
Total Number of Species	≈396, but includes plankton, epifauna species	169	268	239	179	203	235 with Taxonomic Serial Numbers (TSN's)	
Mean Abundance	Not applicable, presence/ absence sampling only, abundances not recorded	722 m-2	[to be computed]	Mean densities: 1412.5 m-2 to 26985.0 m-2, but Hartwell and Hameedi report mean of 451 m-2(?)	[to be computed]	770 m-2 from all stations [to be computed for just Delaware Bay]	Nearly 9000 m-2	Values to be recomputed
Statistical Methods	n/a, see below	Cluster analysis	EMAP BI	Cluster analyses	Benthic indices	PRIMER MDS ordination and VPI and B-IBI indices	Diversity indices, ordination plots, dominance plots	
Overall Conclusions	1st survey, data exceeded manual analysis, data awaits analysis (2011)	Low abundance implies low productivity, faunal assemblages better related to sediment than salinity	One-fourth of the Delaware Estuary has impacted benthic communities	Diversity and abundance lowest in low salinity dominated by tubificids and oligochaetes; species richness correlated with grain size	One-third of Delaware Estuary received poor score using Paul et al. (1999) benthic index (EMAP-VP)	Ordination suggests salinity and latitude subregions; NCA data with VPI: 34% good, 29% poor, 37% missing	Salinity drives distribution and diversity overall	Distinct estuarine fauna as in, e.g., Remane diagram, but recent studies discount existence of true "estuary species" and interpret distribution and assemblages in light of salinity, sediment and stressors
Key References	Amos (1952, 1954 and 1956) but largely unpublished	Maurer et al. (1978), Kinner et al. (1974)	Billheimer et al. (1997), Billheimer et al. (2001)	Vittor (1998), Hartwell et al. (2001) Tech Memo 148	USEPA 2002; EPA/ 620/ R-02/ 003	Hale (2011)	[This report is the first look at these data]	
Web URL for Data	Digitized, awaiting analysis	Results published, availability of raw data unknown	http://www.epa.gov/emap/html/data/geographic.html	http://ccma.nos.noaa.gov/about/coast/nsandt/download.aspx	http://www.epa.gov/emap/maia/html/data/estuary/9798/index.html	http://www.epa.gov/emap/nca/index.html	http://www.delawareestuary.org/science_projects_baybottom.asp	

topics. These results also furnish an important baseline for tracking future ecosystem responses to changing climate and continued development in the watershed.

A top priority of this project was to use standard methods to examine the spatial distribution and relative abundance of bottom communities living in soft-bottom substrates that span the broad salinity gradient of the Delaware Estuary. Sediment chemistry and water quality were also examined at the same sample stations. A second priority was to explore biological communities living on selected hard-bottom habitats. Although the RARE-funded (Regional Applied Research Project) project, through USEPA, was of foundational importance in launching the program and furnishing base layers, follow-up studies are planned to continue DEBI, such as further exploration and mapping of hard bottom communities and mapping of benthic ecosystem services.

By creating a biological layer, to complement existing habitat and bathymetry layers, insight can be gained to the benthic communities that inhabit the Bay and River. Benthic invertebrates tend to live a longer life than most planktonic organisms and can therefore suggest the environmental conditions over time. The Delaware Bay and River consist of both hard bottom and soft bottom, each revealing different knowledge. The soft bottom is a dynamic system that can reveal information about anthropogenic inputs, the history of anthropogenic changes caused to hard bottoms in the lower Bay, and the legacy that it has left is also of relevance. These changes have possibly lead to compositional and structural changes to the biological communities.

As a first step in launching DEBI, the Partnership for the Delaware Estuary (PDE) partnered with United States Environmental Protection Agency (USEPA) Regions 2 and 3, USEPA Office of Research and Development, and other academic and agency partners to create a technical work group affiliated with the PDE Science and Technical Advisory Committee. PDE and this work group held workshops and summarized existing benthic data from seven prior bay-wide scientific studies. In addition, specimen collections from surveys by William Amos and colleagues in the 1950s were retrieved from storage and digitalized to augment the growing compendium of existing benthic information.

The soft-bottom survey was completed during the summer of 2008, consisting of 230 sampling sites from the mouth of Delaware Bay to the confluence of the Schuylkill and Delaware River, stratified by three salinity zones and sampled using a probabilistic design. USEPA Region 3 provided critical in kind support for the 2008 cruises, including ship time and staffing. Bottom grab samples were taken at each station and split for biological taxonomic examination and chemical analyses. USEPA Region 3 analyzed samples for a suite of sediment chemistry parameters, and the Delaware River Basin Commission examined splits samples for PCBs. Macroinvertebrate analyses were conducted via a subcontract to Versar Inc.

Exploratory surveys of selected hard bottom habitats were conducted in 2008, 2009 and 2010. Hard bottoms are more difficult to survey than soft bottoms in the Delaware Estuary because of naturally high turbidity and the ineffectiveness of grab samplers used for soft bottoms. Consequently, much less is known about these areas despite the belief that they are biologically active and ecologically important. Epibenthic sleds, oyster dredges, divers, and remotely operated underwater vehicles (ROVs) were used, where possible, yielding important new information for areas that were surveyed. For example in the lower Bay, extensive "sponge gardens" and worm reefs were found in deeper troughs using the dredge, and divers observed greater fish use of these complex habitats compared to adjacent sand soft-bottoms. In the freshwater tidal zone of the estuary, at least two types of Submerged Aquatic Vegetation (SAV) and seven species of scarce or rare unionid mussels were discovered in substantial abundance. Two of the mussel species were considered locally extinct by state agencies. These discoveries of sensitive, rare biota were unexpected considering that they were found in the urban corridor which has had historically poor water quality. Although further work is needed to examine their range and abundance, these beds of freshwater mussels and SAV (which coexisted in many areas) could be important for sustaining fish habitat and water quality in the upper Estuary.

Taken together, results from the soft- and hard-bottom surveys have yielded important discoveries and provided the most spatially complete biological layer ever for the bottom of the Delaware Estuary. The new biological layer clearly shows that bottom communities of the Delaware Estuary are spatially complex, spanning the many salinity zones and influenced by the presence and absence of sediment chemistry and stressors. From this layer climate change scientists will have a comprehensive baseline to track future changes in biological communities. The Delaware Estuary has over 200 migrant and resident finfish species that use the Estuary for feeding and spawning, and these new data will also provide managers with a better geospatial understanding of how benthic food resources and habitat support fisheries productivity and/or critical habitat for endangered species such as sturgeon. Maps of filter-feeding organisms may lead to a better understanding of pelagic-benthic coupling and ecosystem services that benefit water quality. Certain hard-bottom communities such as intertidal *Sabellaria* reefs and shallow subtidal oyster reefs are also increasingly appreciating for helping offset storm surge and coastal flooding.

The work supported by the RARE grant greatly increased our understanding of the estuary's bottom ecology and will have a direct bearing on diverse management priorities. More effort will be needed to build on the DEBI data to increase our understanding of benthic processes, hard-bottoms, and temporal (seasonal or inter-annual) variability that occurs across the Delaware Estuary. To track anthropogenic and climate driven changes, the benthic biota should also be broadly sampled using comparable methods at least every ten years.

5.1.2 Description of Indicator

Because of their abundance, diversity, sessile nature and recognized responses to environmental conditions, benthic organisms have long been used to assess the "health" of estuarine systems. In this context, the responses of the benthos to disturbance, organic enrichment associated with eutrophication and pollution, including oil and heavy metals, are of particular interest. To obtain benthic faunal data, typically a grab sampler is used to retrieve a bottom sample, and the sample is subsequently sieved to retain animals, which are then preserved. In the laboratory, macrofauna are identified, enumerated and weighed, allowing metrics such as the number of species, diversity indices or other statistical comparisons of stations to be computed. Examinations of patterns in these metrics are then used to infer the state of, or trends in, the benthic community. Alternatively, direct comparison of assemblages between impacted and reference sites may be used to infer habitat degradation and by extension the overall state of the benthic system.

The condition of the benthic community is well known to respond to physical (especially salinity and sediment properties such as particle size) and biological (primary productivity, food web structure, especially predators) factors as well as to chemical stressors (e.g., organic enrichment, metals, oil and other organics). Typically, estuaries are spatially and temporally variable in these physical, biological and chemical factors, and benthic species abundance and assemblage composition is accordingly found to be highly variable in time and space as well. In addition, the faunal or assemblage response(s) to a given factor are often not unique, that is, an observed change cannot always be associated with a single causative agent (i.e., chemical), trend or process, whether natural or anthropogenic. Polluted sites may have assemblages resembling that of naturally disturbed sites and to complicate matters further, stressors may act in combination, and cause and effect may thus be difficult to resolve using simple measures, especially where observed differences are embedded within the overall natural variability of the estuarine environment.

2012 was the first time an analysis of the subtidal benthic community was used as a metric in the State of the Estuary report. Below, we review sampling of the Bay conducted under the aegis of the Delaware Estuary Biotic Inventory (DEBI) project and present some preliminary findings and conclusions. These results are then placed in the context of past surveys and followed by some consideration of the use of historical surveys for assessing trends across decadal time scales.

5.1.3 Present Status

In summer 2008, the Delaware Estuary Benthic Inventory (DEBI) was conducted. To gather soft-bottom benthic data, extensive benthic grab and water column sampling was conducted throughout the Delaware Bay and River at 229 sites allocated in a design based on random locations within salinity and bottom sediment strata. Sediments were sampled using a 0.04-m^2 modified Young grab, sieved on a 0.5-mm mesh, and processed. A summary of environment parameters measured during this survey is presented in Table 5.1.2. Benthic species composition, sediment characteristics and measurements of metal concentrations as potential stressors were analyzed using diversity indices, multivariate ordinations, and dominance curve techniques.

Overall, 233 benthic species were identified in 112 families and 9 phyla. Five stations had 40 or more species and the mean species richness (number of species) was 13. The most diverse groups were: polychaetes (27 families, 79 species), amphipods (15 families, 35 species), bivalves (17 families, 27 species), and gastropods (15 families, 25 species). The mean benthic invertebrate abundance was 8,800 individuals per square meter. The greatest total abundance was 142,000 individuals per square meter at Egg Island Point; this abundance was dominated by the polychaetes, *Sabellaria vulgaris* and *Polydora cornuta*. The most abundant single species at any station was the bivalve, *Gemma gemma* (71,000 individuals per square meter) near Nantuxent Creek. The dominance by polychaetes, bivalves and amphipods was expected for the estuary's mixed sand-silt sediment as well as from previously published studies, although the abundances reported here are considerably larger than some previous reports (as discussed below). Together, the DEBI data represent the most intensive and comprehensive assessment of the Delaware Estuary's benthic fauna ever conducted, and these data are especially valuable in comparison with surveys of Delaware Bay conducted in the 1950's, 1970's and more regularly since 1990 (Table 5.1.1, page 162).

Figure 5.1.2 displays the estuary-wide patterns of benthic species diversity. Species richness (number of species) versus bottom salinity (Fig 5.1.2A) and river mile (Fig 5.1.2B), with approximate demarcations of polyhaline, mesohaline, oligohaline and tidal freshwater zones. Both plots show a characteristic shape of a Remane diagram (Remane and Schlieper 1971) where the pattern is of high diversity at the Bay mouth (and

Table 5.1.2 Summary of benthic Surveys in the Delaware River and Estuary conducted 1951-2008. (< D.L. means below the detection limit).

Parameter	Mean	Minimum	Maximum	Units
Salinity	13.3	0.2	31.8	‰
Temperature	24.8	17.1	27.8	°C
Dissolved Oxygen	6.8	4.3	11.8	mg/l
pH	7.7	7.0	8.5	-
Turbidity	41.3	3.4	919.2	NTU
% Sand	58.4	0.8	98.8	%
TOC	1.6	< D.L.	7.8	%
Arsenic	7.35	< D.L.	330	µg g-1
Cadmium	0.44	< D.L.	4.6	µg g-1
Chromium	23.7	1.1	132	µg g-1
Copper	13.5	< D.L.	112	µg g-1
Lead	22.6	1.4	256	µg g-1

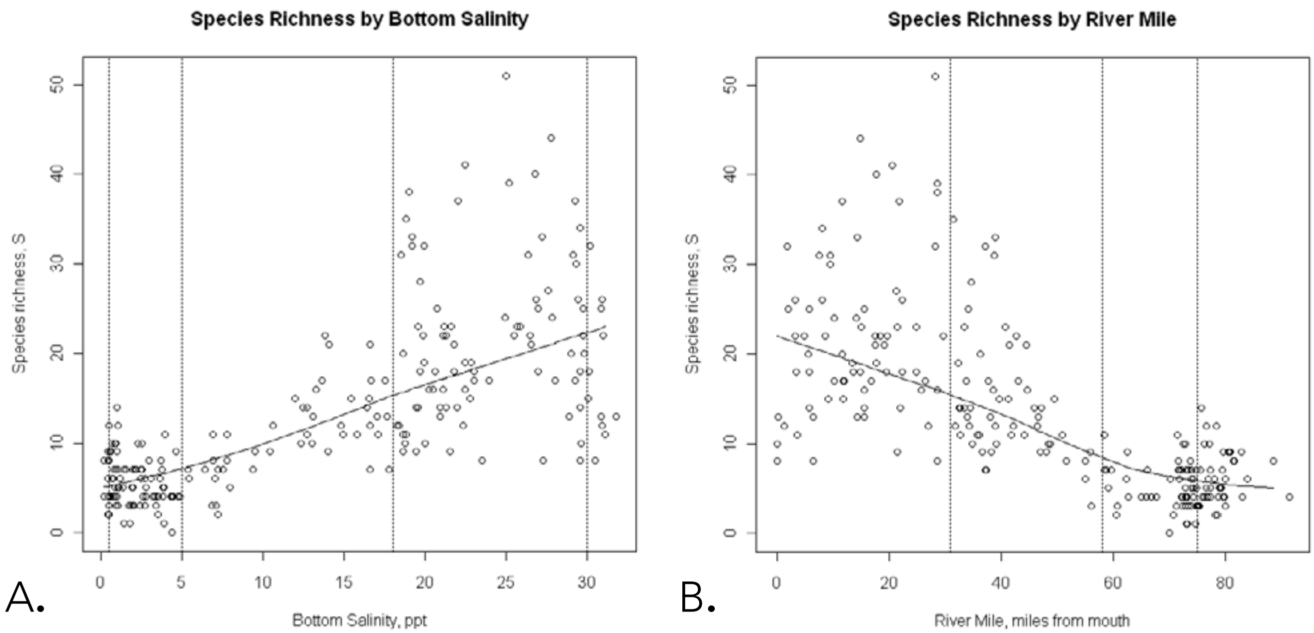

Figure 5.1.2 Patterns of benthic species diversity, comparing species richness versus A) bottom salinity and B) river mile.

at high salinity), decreasing upstream into the mesohaline, reaching a minimum, then higher (and here, more variable) in the oligohaline (near 80 miles from the Bay mouth). This is the pattern of benthic diversity commonly seen across estuaries and described in marine ecology textbooks, see Levinton (2001) or Kaiser et al. (2005) and references therein. Figure 5.1.3 shows benthic diversity in a spatial context using another commonly used metric, the Shannon-Wiener diversity index, H'. The interpretation of this plot is similar to those above: the concentration of red and orange dots in the Lower Bay suggests higher diversity there as compared to the riverine sections of the Bay denoted by green and black dots.

Figure 5.1.4 is a species accumulation curve showing the number of species expected versus number of samples taken in the DEBI survey; as more samples are taken, more species are recorded. A leveling off of this curve would indicate that few new species would be recorded by additional sampling, and thus the asymptote represents the total diversity as number of species in the estuary. The shapes of these curves (i.e. initial slope and asymptote) can be compared among studies in order to gauge the effectiveness of sampling and assess the degree to which the full diversity has been sampled. The upward slope at the right of the DEBI curve shown here indicates that even this extensive survey did not capture the full (technically, alpha) diversity of the Delaware Bay soft-bottom benthos. However, the observed diversity of 233 species is generally consistent with other surveys summarized in Table 5.1.1.

A more detailed view of the estuary's benthos is provided using a non-metric multidimensional scaling (MDS) ordination of the full species by assemblage abundance matrix. Figure 5.1.5 shows all 299 stations' similarities based on all 233 species using fourth-root transformed abundances and the Bray-Curtis similarity metric, computed using the PRIMER-E package (Clarke and Warwick 2001, Clarke and Gorley 2006). Each symbol represents a station: symbols close together have similar species composition (low dissimilarity), while points far apart differ in species composition (i.e. are dissimilar) in accordance of their separation. The stress value reported here, 0.13, indicates that the two-dimensional plot adequately represents the multivariate (high-dimensional) dissimilarities among stations. The broad ellipses represent groups of stations determined as by a cluster analysis as superimposed on the ordination and are show here for visual reference. When stations are coded by salinity zone (Fig 5.1.5A) it is clear that benthic assemblages relate

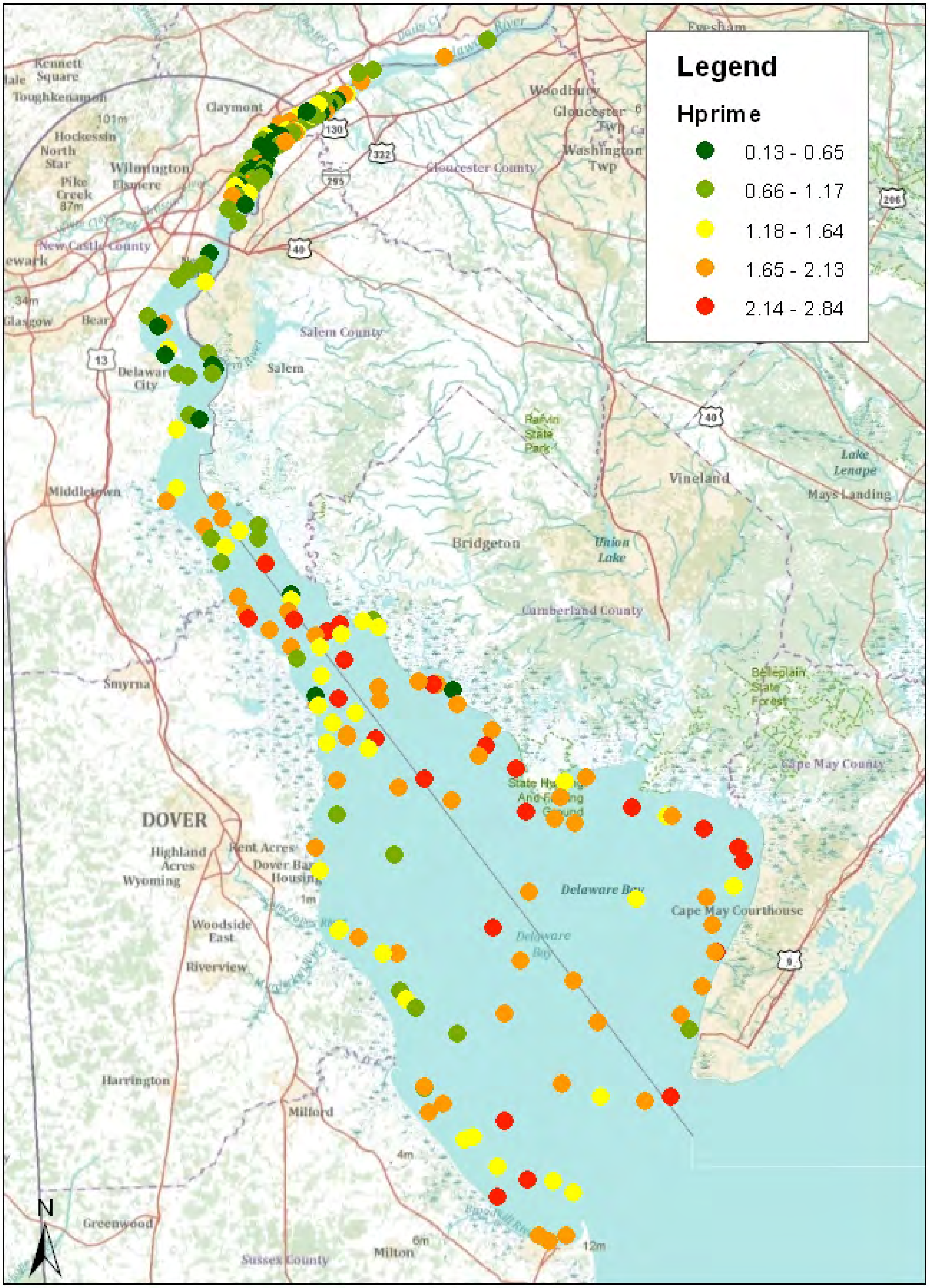

Figure 5.1.3 Dots show DEBI sampling locations, and are colored to show benthic diversity in a spatial context, using the Shannon-Wiener diversity index, H’ (Hprime).

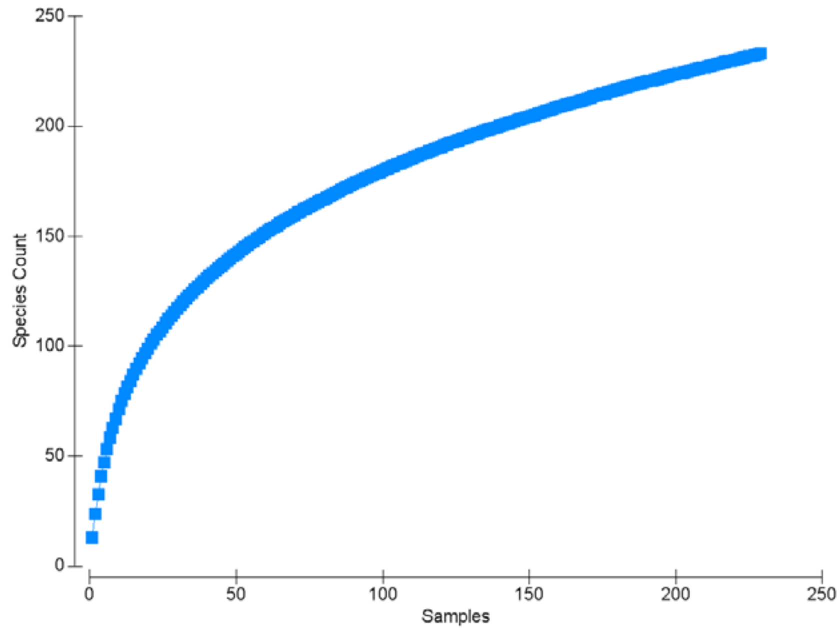

Figure 5.1.4 Species accumulation curve, number of species versus number of samples taken during DEBI project.

to salinity, with freshwater and oligohaline stations grouped together on the left, mesohaline concentrated in the middle and polyhaline and euhaline falling together to the right. Figure 5.1.5B is the same ordination (i.e., the pattern of station points is identical), but the color key represents sediment grain size measured as percent sand. Sandy, silty-sand and silty sites are not separated, but intermixed and not clearly related to species composition, thus sediment composition is not simply associated with broad patterns in species composition. As was found using simple diversity metrics, salinity is the dominant factor correlated with benthic community structure.

Additionally, MDS ordination plots of benthic assemblages can be used to investigate the benthic response to stressors. Figure 5.1.6 shows four such ordinations (with points identical to those already shown) with the symbol size representing the level of each of two potential stressors: dissolved oxygen near bottom and total organic carbon. Figure 5.1.7 shows another two potential stressors: cadmium and chromium. Dissolved oxygen measured near the bottom was in all cases 4.4 mg/l or greater (Table 5.1.2), and it is not surprising that there is little association of bubble size with stations clusters or broad patterns in the ordination in figure 5.1.6A. Total organic carbon show larger bubbles associated with stations in the upper and lower Bay (Fig 5.1.6B), likely associated with fine sediments (compare with Fig 5.1.5B). A distinct association of high metal concentrations and benthic assemblages and stations is apparent in both figures 5.1.7A and 5.1.7B as a knot of large bubbles associated with lower salinity stations (Fig 5.1.5B). This suggests that metal concentrations may be affecting benthic assemblages at these stations and that further analysis is warranted.

Dominance curves can likewise be used to investigate patterns in benthic fauna. Potentially disturbed or polluted assemblages have been found to be dominated by a few but abundant species (Warwick 1986, Warwick and Clarke 1994, Elliott and Quintino 2007). Figure 5.1.8 shows these lots for DEBI species data pooled by salinity (A) or sediment class (B) or both jointly (Fig 5.1.9). The plots show the cumulative percent of individuals for the most abundant species, the second most and so on, by species. A gradual rise to 100% is apparent for these categories, for all sediment classes (Fig 5.1.8B) and mesohaline, polyhaline and euhaline classes, while oligohaline and freshwater curves show higher dominance, higher curve on the left side (Fig 5.1.8A). When jointly classified (Fig 5.1.9) the oligohaline-silt and fresh-silt stations show high dominance, considerably greater than that of the rest of the salinity-sediment classifications.

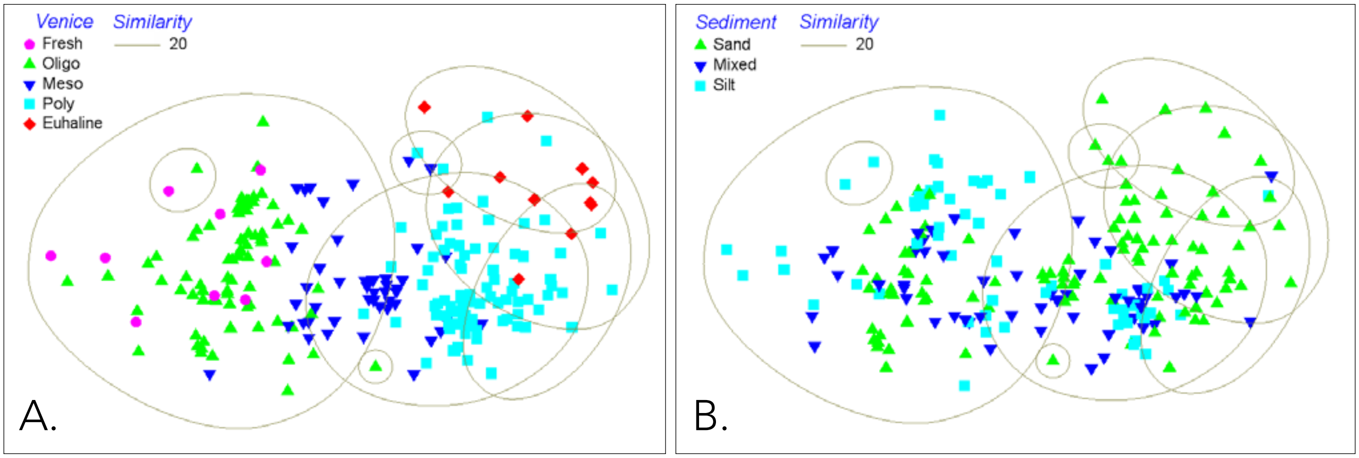

Figure 5.1.5 MDS ordination analysis showing species similarities based on A) salinity zones and B) sediment types.

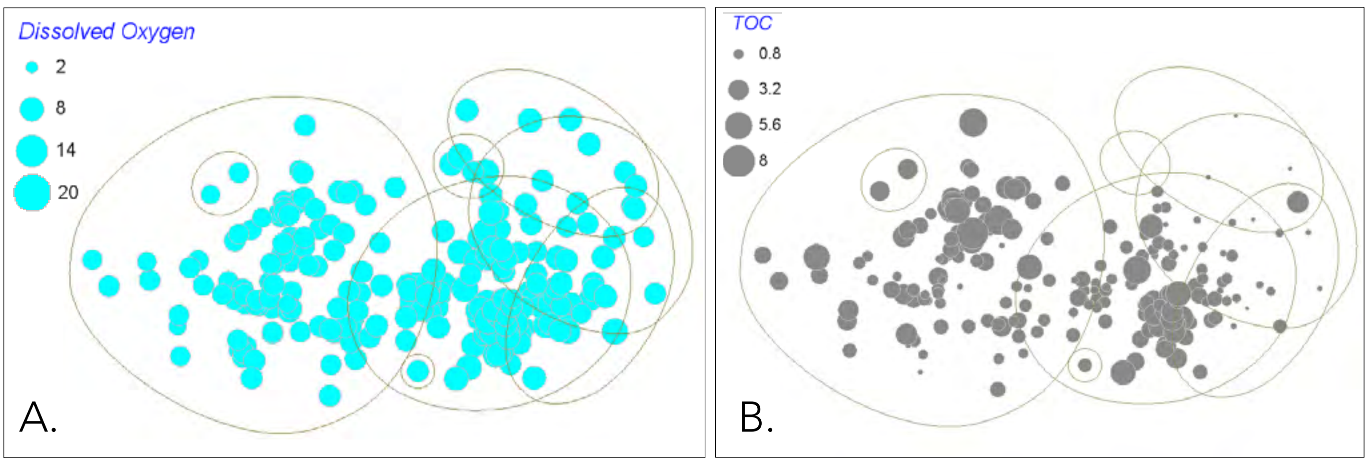

Figure 5.1.6 MDS ordination analysis showing species similarities based on A) dissolved oxygen concentrations and B) total organic carbon.

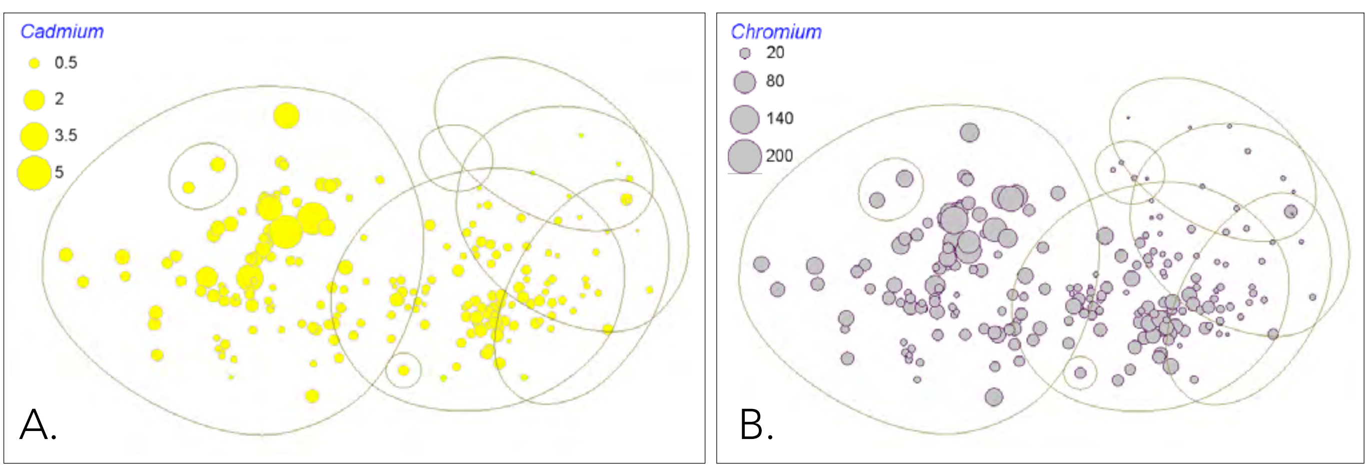

Figure 5.1.7 MDS ordination analysis showing species similarities based on A) Cadmium concentrations and B) Chromium concentrations.

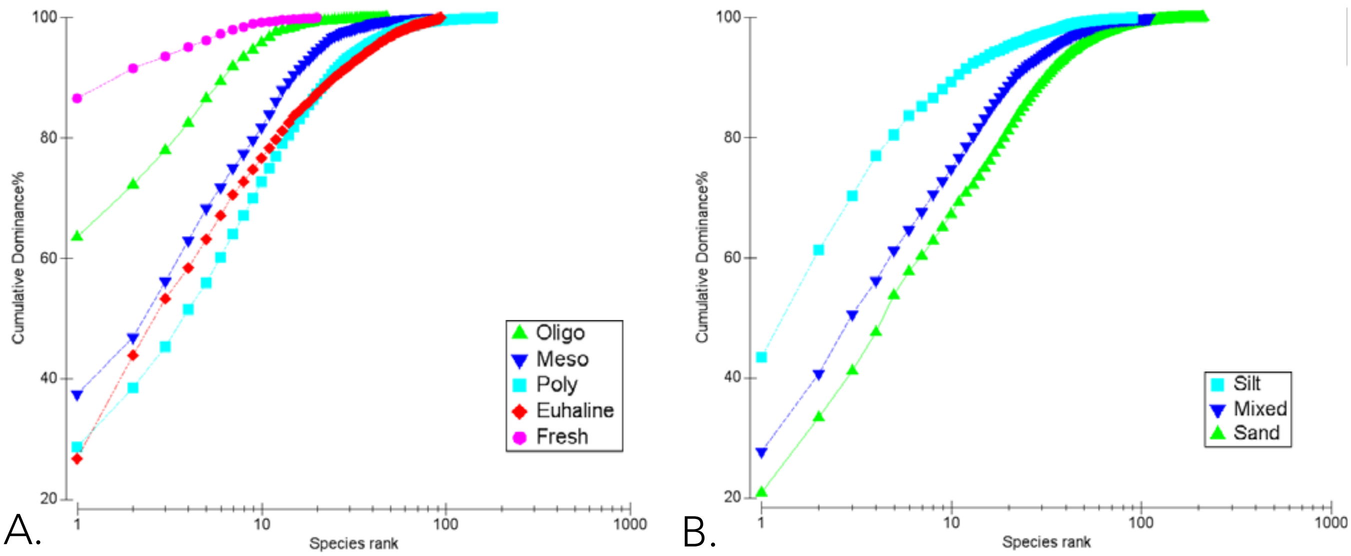

Figure 5.1.8 Dominance curves for DEBI species data, pooled by A) salinity and B) sediment class.

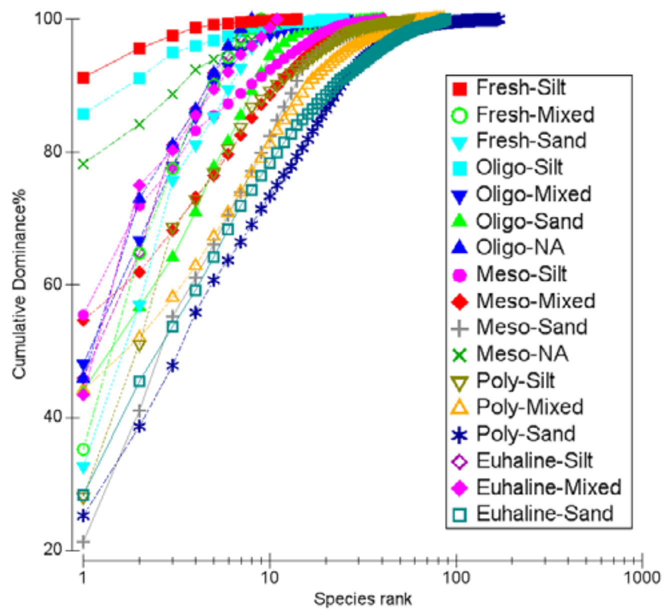

Figure 5.1.9 Dominance curves for DEBI species data pooled by salinity and sediment class.

Biomass curves can also be used to identify disturbed or polluted conditions: the cumulative percent biomass by species rank is superimposed on the dominance curve in a combined abundance-biomass comparison (ABC; Fig 5.1.10) plot. In unpolluted conditions, the biomass curve lies above the abundance curve (Warwick 1986, Warwick and Clarke 1994, Elliott and Quintino 2007), representing an assemblage with many species of moderate abundance and biomass dominated by a few large species, and this interpretation is consistent with that of the classical Pearson and Rosenberg (1978) paradigm (see also Gray and Elliott 2009). In disturbed or polluted conditions, a few but abundant, yet small species dominate (i.e., the large species are eliminated), and the abundance curve lies above that of the biomass. For the DEBI data, fresh and silt ABC curves (Figs 5.1.10A and 5.1.10B) are inverted, in comparison to mesohaline and sand (Figs 5.1.10C and 5.1.10D). Inversion of the ABC curves is also clearly apparent in the fresh-silt and oligohaline-silt curves (Figs 5.1.10E and 5.1.10F), and these stations are located in the C&D Canal to state-line region (and

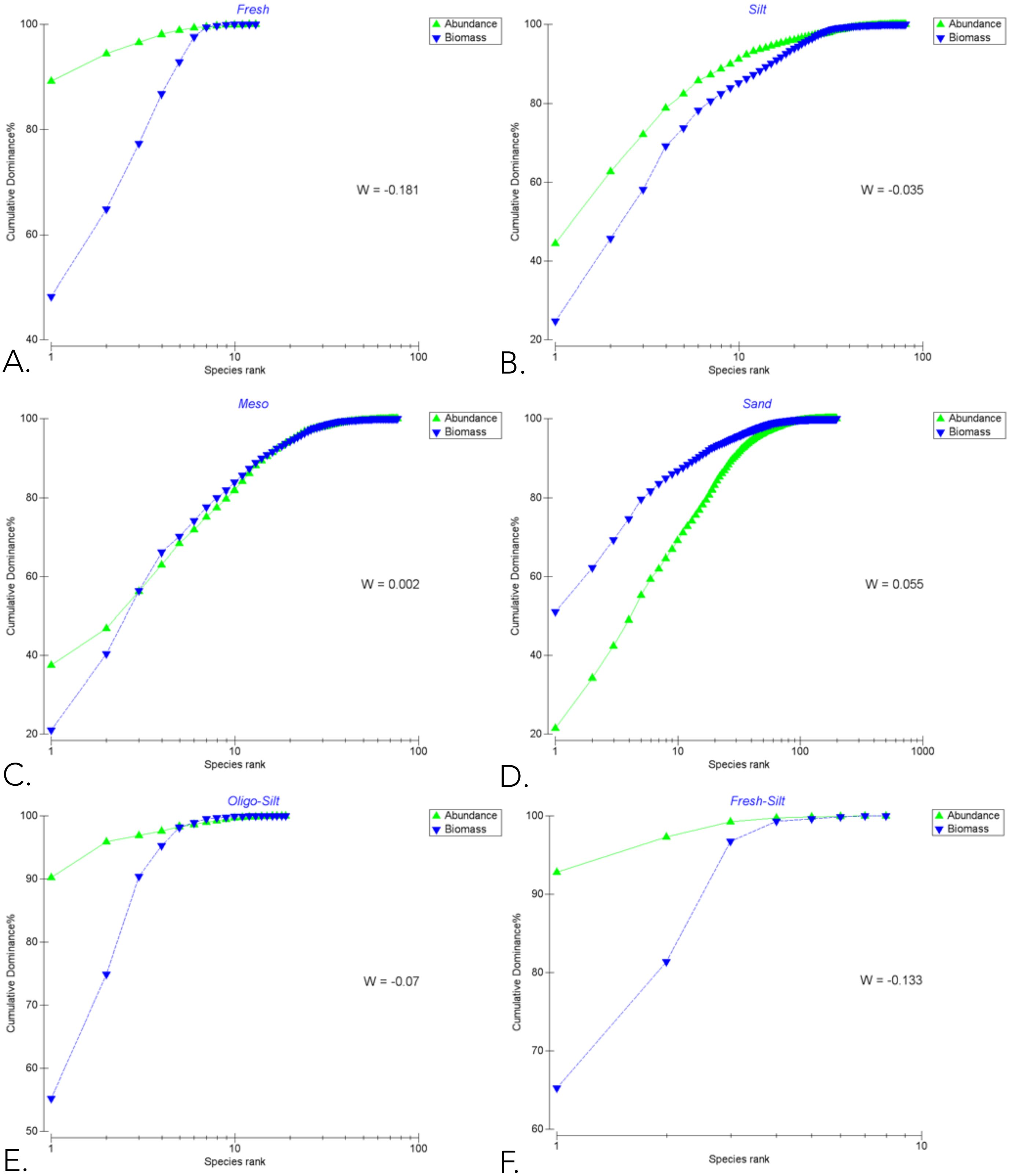

Figure 5.1.10 Abundance-biomass curve for A) freshwater stations B) silty sediment stations, C) mesohaline stations, D) oligohaline and sandy stations, E) oligohaline and silty sediment stations, and F) fresh-silty sediment stations.

within DRBC's Zone 5) of the estuary. Especially as this area has been characterized as degraded in benthic condition in past studies, these patterns at these stations merit further investigation.

The conclusions from this analysis are that broad-scale estuarine patterns are as expected for a temperate Atlantic estuary and that the soft-bottom benthic diversity of the Delaware has been sampled to a reasonable though, not exhaustive, extent. Bay-wide, salinity drives the patterns among benthic assemblages to a greater degree than sediment composition, and that high metal concentrations are associated with assemblages at certain stations. Further analysis within salinity and sediment classes reveals assemblages highly dominated by a few, abundant species, which also exhibit inverted abundance-biomass curves, further suggesting disturbed or polluted conditions. In summary, while these overall patterns among the benthic fauna are as expected in terms of abundance, diversity and biomass, stations in the C&D Canal to state line region (DRBC's Zone 5) are distinct in their assemblages, associated with high metal concentrations and have abundance and biomass curves consistent with polluted conditions. This region has been characterized as degraded in past studies on benthic assemblages.

5.1.4 Past Trends

Starting in the early 1950's, there is an extensive history of scientific benthic study in the Delaware River and Estuary (Table 5.1.1). Since 1990, surveys have used probabilistic designs for station selection (i.e., Fig 5.1.3) as well as consistent methodologies for sample collection and processing, faunal identification and taxonomy, and data summary and compilation. Specifically, there have been five separate federal programs using the benthos as indicators in Delaware Bay. Conclusions from the early 1990 Environmental Monitoring and Assessment Program (EMAP) survey are reported in Sutton et al. (1996). According to the EMAP benthic index, 93% of the area of the tidal river has benthic communities classified as degraded (68% area) or severely degraded (25% area, see Sutton et al. 1996 Fig 7-14 on page 116). In comparison, only 2% of the Bay's area south of the C&D canal was degraded, and no stations were severely degraded. Several benthic indices have been applied to Delaware Bay stations as part of the broader-scale, National Coastal Assessment (NCA) studies beginning in 2000. Using the Virginian Province Benthic Index and 2000-2001 data, 34% of the stations were rated "good," 29% "poor," and 37% "missing," and this mixture of conditions was found throughout the Bay and River (USEPA 2006).

In addition to the federal studies, there are "historical" surveys undertaken by Amos in the 1950's and Maurer and colleagues in the 1970's (Table 5.1.1). In total, sampling has been reported at nearly 900 stations, and the total number of species reported from these studies is consistently 200 or more (cf. Fig 5.1.4), with the mean (over stations) total abundances (number of organisms per meter squared) in the expected range of 1000 – 10,000 per square meter, although two surveys reported abundances well below 1000 per square meter. In particular, low abundances were noted by Maurer et al. (1978), wherein they concluded that low abundance reflected low benthic productivity in the Delaware Bay. Low abundance could equally be explained by their use of a 1-mm mesh sieve as compared to the 0.5-mm mesh (a smaller sieve retains more, smaller fauna) used in the present DEBI 2008 sampling as well as other recent federal surveys), although Maurer et al. (1978) discuss this point and explicitly discount this explanation in their report. The reason(s) for the low mean abundance reported by Hartwell and by Hale are not resolved at present. Future studies by comparing abundance of large species and small (i.e., those not expected to be completely retained by a coarse sieve) selectively, may make it possible to confirm a sieve-bias explanation for at least the Maurer et al. (1978) results.

All or most of the federal data are hosted online although distributed over several federal agency web sites and presented in various data formats. In most cases, data are tabulated as species abundances, and fortunately the consistency of sampling, laboratory analysis and ready availability of these data will allow synthesis by modern statistical techniques. Any trends in these data over the past 30 years should be resolvable once challenges of data formatting and merging are overcome.

5.1.5 Future Predictions

Summary plots of diversity, faunal assemblage ordinations and dominance plots above show that likely sufficient sampling has been conducted to facilitate development of conclusions and that broad, estuary-scale patterns are as expected based on typical estuarine patterns of diversity. It is important to note that the federal agencies have routinely included stressor variables, such as dissolved oxygen, organic carbon, heavy metals and organic pollutants in their measurement suite (Table 5.1.2). These individual surveys have consistently assessed the benthos in light of possible stressors, yet there have been few if any attempts at cross-survey synthesis of these data to assess trends in benthic community structure and condition over time.

5.1.6 Actions and Needs

The ready availability of extensive data clearly justifies a cross-survey analysis of the past 30 years. Additional effort will be required to determine if differences among data sets are due to a sampling design (spatial allocation of locations) or sampling gear-bias (especially sieve mesh size) or truly represents significant change in estuary conditions. Only limited, broad conclusions can be drawn from the simple data summaries and plots presented here. Further analyses using multivariate methods like multi-dimensional scaling and dominance curves may reveal patterns and relationships impossible to discern among multiple possible natural variation and anthropogenic effects. Effective analysis of these benthic data will require additional effort to identify sensitive and tolerant species, reference and control sites (to develop customized and calibrated indices), and the application of more sophisticated multivariate, phylogenetic/taxonomic structural analysis or regression-based species distribution modeling.

5.1.7 Summary

The benthos of Delaware River and Estuary has been extensively studied and well characterized in surveys conducted over the past 60 years. The most recent, 2008 DEBI survey, represents a firm baseline demonstrating patterns in diversity similar to those found before and typical of temperate estuaries. Overall patterns among the benthic fauna are as expected in terms of abundance, diversity and biomass, but stations in the C&D Canal to state line region are distinct in their assemblages and associated with high metal concentrations. The current DEBI survey data are consistent with other recent studies employing standardized methodology and refute previous conclusions that the Bay's fauna is depauperate and unproductive. The availability and congruence of several previous data sets with the current DEBI results clearly justifies a cross survey analysis of all of the data from the past 30 years. Further effort will be required to determine if perceived differences may be due to sampling gear-bias issues, sampling locations differences, or represents real and significant changes in estuary conditions. Effective analysis of these data will require additional effort to identify sensitive and tolerant species, reference and control sites, and the application of more sophisticated multivariate, structural (i.e., phylogenetic/taxonomic) or regression-based species distribution modeling.

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Suggested Citation for this Chapter

Miller, D., A. Padeletti. 2012. "Chapter 5.1 - Subtidal Habitats" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 161-174.

5.1.8 Delaware Bay Benthic Mapping Project

Bartholomew Wilson, P. G., PhD • North Atlantic Coastal Resiliency Coordinator • U.S. Fish and Wildlife Service

Through an integrated effort by the Delaware Coastal Programs and the University of Delaware, a benthic and sub-bottom imaging project to identify and map the benthic habitat and sub-bottom sediments of Delaware Bay and River was initiated in 2004. This project would not have been possible without the following partners: University of Delaware Geosciences Department, Delaware Fisheries Section, Delaware Shoreline and Waterway Division, Delaware State University, Partnership for the Delaware Estuary, New Jersey Department of Environmental Protection, and New Jersey Shellfish Bureau.

This project integrates the use of three types of acoustical systems: Roxann Seabed Classification System, CHIRP sub-bottom profiling, and multi-beam bathymetric mapping. Verification of the acoustic data with bottom and sub-bottom sediments is performed through the collection of grab and core samples and underwater video images.

This effort has resulted in many major milestones, which include: mapping over 906 square km, identifying the spatial extent and relative density of the oyster and *Corbicula* beds, identification of borrow sites for beach replenishment, facilitating a greater understanding of the local and regional sediment distribution patterns and pathways, locating key habitats for species (such as: Atlantic Sturgeon, sharks, and *Sabellaria vulgaris*), and starting to understand the relative impact that humans have upon the bay bottom and its living resources. Most importantly integrating the bottom and sub-bottom sediment with species tracking information, in a 3D GIS environment, has provided a new opportunity to assess the habitat relationship between Atlantic Sturgeon and several key regions in the Delaware River.

The program has many accomplishments including an integration of the benthic and sub-bottom data was used to identify sand borrow sites within the Delaware Bay that are located in areas that minimize the impact upon essential fish habitat (especially *Sabellaria vulgaris* habitat). Borrow sites have been located for three coastal communities, and will determine sand resources for 4 additional coastal communities. In addition, the project has worked with The Nature Conservancy (TNC) and the Partnership for the Delaware Estuary to develop benthic habitat maps for the Delaware Estuary. In September 2011, TNC produced a report entitled; Delaware River Basin Priority Conservation Areas and Recommended Conservation Strategies (http://nj.gov/drbc/library/documents/DEbasin-priority-areas_2011NFWF.pdf). In Appendix V; Benthic Habitats of The Delaware Bay, an attempt was made to create benthic habitat maps using bathymetry, salinity and seafloor substrate. Maps of Ecological Marine Units were created taking into account species data provided by the DEBI project.

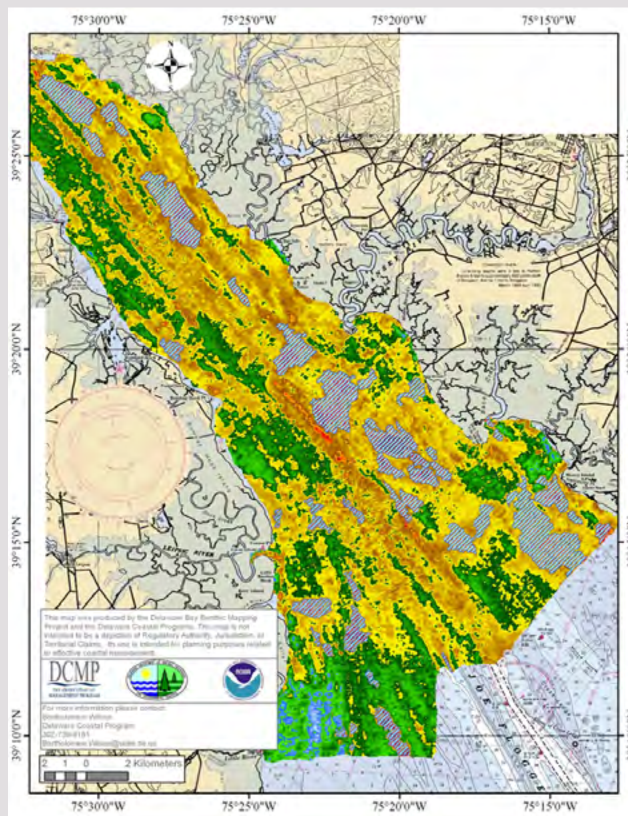

Figure 5.1.8.1 Bottom sediment map showing the distribution of sediments and locations of oyster beds over a 180 square mile area in the upper Delaware Bay Estuary. In this region, 40 distinct oyster beds were located.

5.1.9 Amos Historical Benthic Collection Analysis

Douglas Miller, PhD • Professor • University of Delaware College of Earth, Ocean, and Environment

The Delaware River Invertebrate Collection (DRIC) was the first scientific collection of benthic organisms for the Delaware River and Estuary. William H. Amos' handwritten 5" x 8" data cards along with preserved master specimens from the 1950's are currently housed at the University of Delaware in Lewes. Standing 25 cm (10") high when stacked vertically, these invertebrate cards were scanned for archival purposes in October, 2008 and later digitized.

The Amos DRIC includes over 5,500 records of nearly 400 species from over 130 stations within the Delaware River and Estuary. Information in a locality field in addition to uncovered charts promises to yield much more precise information for sampling locations. These data include collection of benthic organisms by trawl, dredge and Peterson grab, planktonic organisms by net and epifauna as part of the "buoy scrapes" sampling. Chronologically, these data represent mostly the years 1952-54 and 1956, and primarily July and August collections. Many records are included from the DelZoop plankton sampling that occurred several times a year from October 1951 through August 1953.

Amos identified over 400 taxonomic groupings of which about 396 represent species of invertebrates present in the Delaware River and Estuary. This estimate of species number is generally consistent with numbers Amos gave in University of Delaware Marine Laboratory annual reports. Any such "biodiversity" estimate is clearly provisional, depending on updated nomenclature, taxonomic confirmation, and assessment of the influence of sampling effort and gear bias.

Amos summarized his species distribution data in geographical form using a grid of 40 "sectors" including 37 over the main part of the bay from Philadelphia south, in the bay or just outside, plus Rehoboth Bay, Indian River Bay, and the Lewes & Rehoboth Canal. Samples near Joe Flogger and the Leipsic River have the most records, likely reflecting the intensity of zooplankton sampling in that part of the bay. Sectors near Lewes Beach and the Bayside Lab, along the main channel in the lower bay, and at the Shears/ Harbor of Refuge have over 200 records each. Most collections are from the main channel and lower Delaware side, and with the exception of the Nantuxent Point area, far fewer are from New Jersey waters.

In addition to representing a time in the history of the Delaware Estuary before major industrialization and development, these data present a uniquely comprehensive picture in terms of the functional group, life habit, and taxonomy of the fauna of the river and estuary. Hopefully now that this historical data set is digitized, scientists around the region will be able to access it and use it in their studies of the benthic ecology of the Delaware River and Estuary.

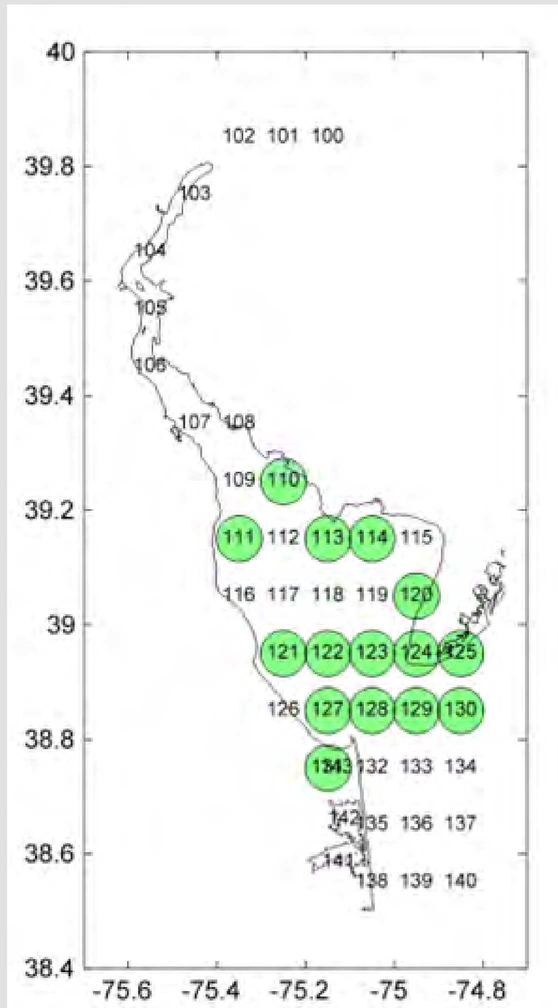

Figure 5.1.9.1 Map of Delaware Bay and Amos' grid used in his pioneering benthic study. Green bubbles show the number of record for the sand builder worm (*Sabellaria vulgaris*).

5.2 Intertidal Habitats

LeeAnn Haaf[1], Danielle Kreeger[1], and Andrew Homsey[2]

1. Partnership for the Delaware Estuary; 2. University of Delaware

5.2.1 Introduction

Tidal wetlands, or marshes, are aquatic habitats which occur in the intertidal zone between open water and upland areas not directly exposed to tidal exchange. Tidal wetlands of the Delaware Estuary extend along both shores spanning the broad salinity gradient from the head-of-tide near Trenton, New Jersey, and down to the mouth of Delaware Bay at Cape May, New Jersey, and Cape Henlopen, Delaware. These habitats undergo daily flooding and draining, and are therefore critical components in the sensitive interaction between land and water in the Delaware Estuary. The traditional definition of a wetland requires that vegetation be present, typically vascular plants. For management purposes, state and federal agencies might also consider many types of non-vegetated aquatic habitats as wetlands, such as shallow ponds, mud flats, and some areas dominated by benthic algae (e.g., Cowardin classification system). But, for the purposes of this report, the principal focus is on vegetated tidal wetlands, which are a hallmark habitat within the Delaware Estuary.

Tidal wetlands are among the most productive habitats in the world and they perform a wide variety of vital services. They are critical to protecting inland areas from tidal and storm damage, provide water storage to protect against flooding, provide important habitat to a wide variety of wildlife, including waterfowl, serve as a filter to remove pollutants and help sustain water quality, provide spawning and nursery habitat to support commercial fisheries, support recreation, and provide aesthetic value. Tidal wetlands are therefore regarded as the most critical habitat type in the Delaware Estuary for supporting broad ecological health. Assuring that these wetlands remain intact and continue to provide these critical functions is therefore fundamental to the protection and the overall quality of the Delaware Estuary and the Delaware River Basin as a whole.

The largest portion of tidal wetlands are composed of salt marshes fringing Delaware Bay, dominated by smooth cordgrass, *Spartina alterniflora* (Fig 5.2.1A). Smaller high salt marsh areas are composed of salt-tolerant grasses (e.g., *Spartina patens* and *Distichlis spicata*) and scrub/shrub vegetation. In the upper estuary and in headwater areas of tidal rivers and creeks, nationally rare communities of freshwater tidal vegetation can be dominant wherever salt concentrations are below 3 ppt (Fig 5.2.1B). These freshwater

Figure 5.2.1 Types of tidal wetlands in the Delaware Estuary: A) salt marsh dominated by smooth cordgrass in Cape May County, New Jersey; and B) tidal freshwater marsh, with spatterdock in the foreground, along Crosswicks Creek, in Mercer County, New Jersey. Photo credit: LeeAnn Haaf and Kathleen LaForce, Partnership for the Delaware Estuary.

tidal wetlands consist of marshes dominated by herbaceous plants (i.e. emergent marshes), but there are some scrub/shrub and forested tidal wetlands as well. Typically, freshwater tidal emergent marshes contain a greater number of species than salt marshes; a few diagnostic species are annual wild rice (*Zizania aquatica*), and low marsh forbs such as spatterdock (*Nuphar lutea*) and arrow arum (*Peltandra virginica*).

5.2.2 Description of Indicator

The science and management community of the Delaware River Basin elevated tidal wetland extent and condition as top priorities for monitoring and management, considering these habitats as one of our leading environmental indicators for the Basin as a whole (Kreeger et al., 2006). Efforts via the Mid-Atlantic Coastal Wetland, established in 2010, to assess the condition (specifically rapid assessments and long term monitoring) of tidal wetlands across the Delaware Estuary have been ongoing (Kreeger et al. 2011).

National Wetlands Inventory Data on wetland distribution were gathered for each state from the U.S. Fish and Wildlife Service (USFWS) National Wetlands Inventory (NWI). The NWI is a nationwide program which seeks to inventory the nation's wetlands. The NWI provides detailed, consistent, high resolution data that enables clear differentiation of wetland types and flooding regimes; however, it is of limited value in trend analyses for the whole system because of the different times that data are collected in different states and areas. For instance, the latest NWI data in New Jersey are from approximately 2002 to the north and 1999 to the south; in Delaware 2009; and new to this report, Pennsylvania in 2015.

Despite shortcomings in the temporal scale, NWI is field verified and provides high quality distribution data on specific wetland types. This makes these data most suitable for assessing the current status of wetlands at the spatial scale. To determine the current extent of the various types of wetlands in the Estuary, the latest of each of three state-wide NWI datasets were categorized using the classification scheme developed by Cowardin (Cowardin, 1979). A simplified classification was developed to allow for a synoptic assessment of status of broad categories with special attention to the differentiation of freshwater and salt water intertidal wetlands (Table 5.2.1).

Land Cover Data Determination of the landscape level changes in different wetland types of the Delaware Estuary requires consistent data in both space and time. Since NWI could not be used for this purpose due to inconsistent temporal scales, changes in wetlands over time (trends) were deduced using land cover data derived from the National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center (CSC). These data are derived from Landsat imagery at a 30m ground resolution.

Categories of wetlands distinguished by the CSC land cover are: Palustrine Forested, Palustrine Scrub/Shrub, Palustrine Emergent, Estuarine Forested, Estuarine Scrub/Shrub, Estuarine Emergent, Unconsolidated Shore, and Palustrine Aquatic Bed. CSC land cover data 1996, 2001, 2006, and 2010 were used. Of these six land cover categories provided by CSC, only one category (estuarine emergent) consists wholly of tidal wetlands (i.e., salt marshes). Although CSC Landsat data are most useful for trend analyses, these data have limited resolution and are not ground-truthed like the NWI datasets. For example, CSC land cover data cannot discern various degrees of flood frequency among wetland types. Previous comparisons of the wetland categories of the CSC land cover data with NWI, however, indicates that the data are comparable to a relatively small percent difference, especially for estuarine emergent wetlands. Therefore, only CSC data were used to assess trends in this tidal wetlands report.

5.2.3 Present Status – NWI Data

Wetlands cover a significant portion of the Delaware Estuary and River Basin (Fig 5.2.2). From expansive salt marsh complexes in the lower part of the Estuary, to isolated wetlands and ponds in the upper riverine reaches, wetlands are an important part of the ecology and hydrology of the watershed. In all, there are 413,000 acres (167,000 hectares) of wetlands (tidal and nontidal) in the Delaware Estuary, representing

Table 5.2.1 Simplified Cowardin classification codes of intertidal wetlands based on NWI categories.

Code	Category	Description
SAITEM	Saline, emergent vegetation	Category includes the typical "salt marsh" characterized by salt tolerant grasses. This is the predominant intertidal wetland type in the Delaware estuary.
SAITV	Saline, other vegetation	Vegetation other than salt-tolerant grasses, including scrub/shrubs and forest. Typical "high-marsh" habitat.
SAIT	Saline, not vegetated	Non-vegetated intertidal area. Comprises mudflats, pannes, unconsolidated shoreline, and beaches. An increase in this indicator typically accompanies a degradation of salt marshes, due to vegetation loss, subsidence, and/or sea level rise.
FRITEM	Fresh, emergent vegetation	Typical fresh water tidal wetlands characterized by emergent vegetation. Generally occur farther up the estuary, or landward of salt marshes in the lower estuary.
FRITV	Fresh, other vegetation	Fresh water tidal wetlands, including scrub/shrub and forested wetland types.
FRIT	Fresh, not vegetated	Non-vegetated fresh water tidal wetlands. Generally comprises only a small portion of intertidal wetlands.

about 5.1% of the total land area. Of all wetlands in the Delaware Estuary, 39.9% (165,000 acres; 66,800 hectares) are tidal wetlands and, of those tidal wetlands, 89.4% are salt marshes. As of 2009, there were a total of 110 million acres (44.6 million hectares or 5.5% of the total land area; USFW, 2011) of wetlands in the conterminous United States, of these, 5% were estuarine. Total wetland density within the Delaware Estuary and River Basin is similar to national values (i.e. 5.1%). Estuarine wetlands within the Delaware Estuary represent nearly 7% of the estuarine wetlands found along the Atlantic sea board, from Maine to the eastern coast of Florida (~2.4 million acres; Dahl and Stedman 2013).

Areas of tidal wetlands will be considered separately by states in which they are found in the Delaware Estuary (PA, NJ, and DE). The following figures illustrate the status of wetland acreage based on the latest NWI data for each state (Figs 5.2.3-5.2.5).

5.2.4 Past Trends – CSC Data

Historical losses in the Delaware Estuary occurred primarily due to the development and conversion of wetlands for agriculture or other purposes. Despite increased regulatory oversight and "no net loss" policies that have greatly slowed rates of wetland conversion, we continue to lose all types of wetlands within the Delaware Estuary and Basin. Indeed, the pace of loss for some types of wetlands might be increasing due to a mix of factors (e.g. sea level rise, climate change, erosion). The focus of this analysis was to examine trends in wetland acreage within the past two decades (1996-2010) because we do not have resources or datasets to carefully document earlier declines.

More than 4,096 acres (1,658 hectares) of palustrine wetlands and more than 2,720 acres (1,100 hectares) of estuarine wetlands were lost in the Delaware Estuary during the fourteen year study period (1996-2010;

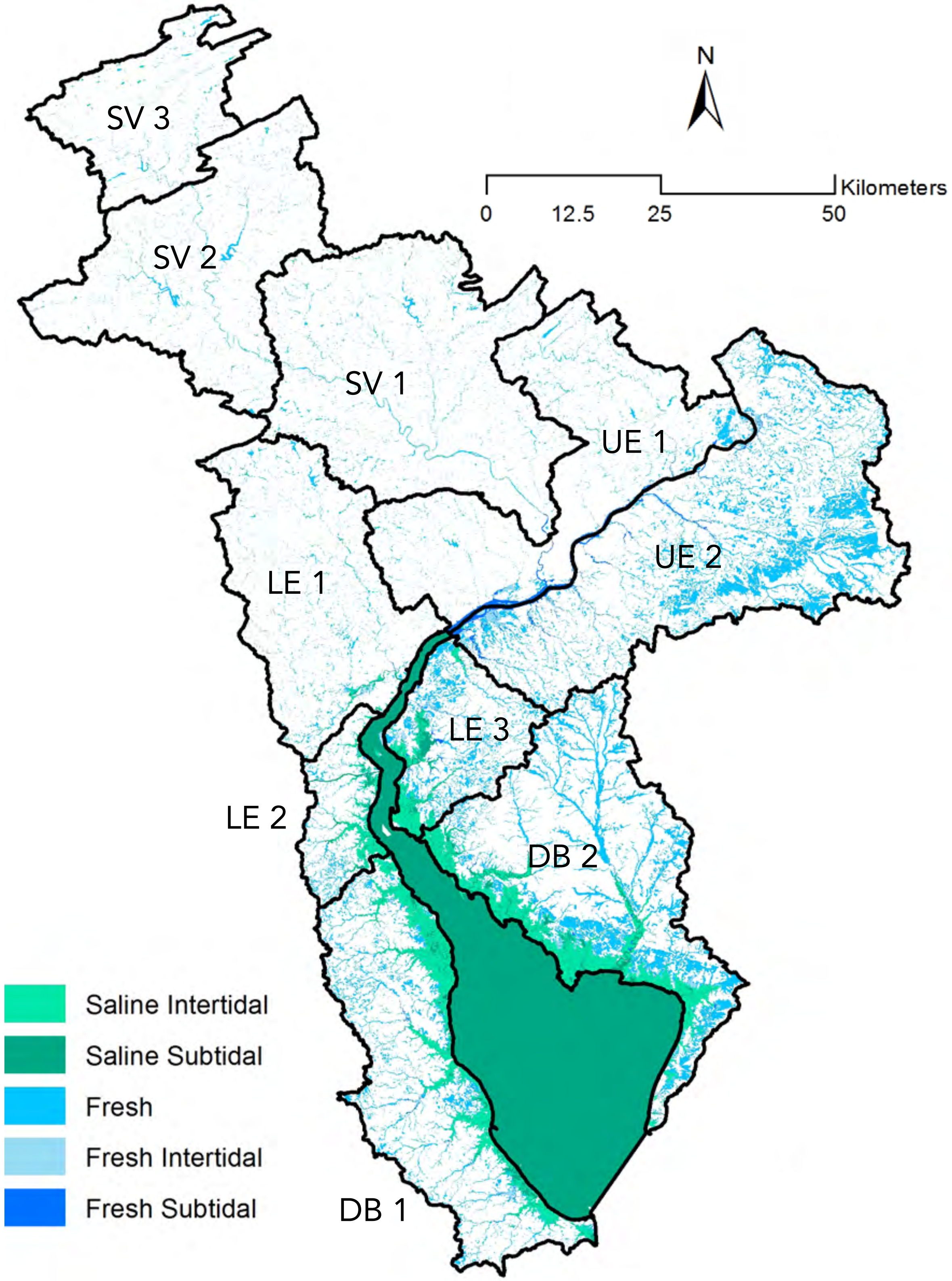

Figure 5.2.2 Latest NWI wetland layer for the lower Delaware River Basin. The estuarine basin was divided into 10 sub watersheds (sub-sheds) which correspond to the Upper Estuary (UE), the Schuylkill Valley (SV), the Lower Estuary (LE), and the Delaware Bay (DB).

Table 5.2.2 and Figures 5.2.6-5.2.7). Although losses in the Upper Estuary add up to smaller acreage, losses are proportionately larger, and they are nevertheless important considering their benefits to people, fish and wildlife, and water quality in the urban corridor.

Between 1996-2010, tidal wetlands have declined in acreage across the delaware Estuary, including both palustrine (-1.02%; -293 acres or -119 hectares per year) and estuarine (-1.77%; -194 acres or -79 hectares per year) wetlands (Table 5.2.2). The largest estuarine wetland losses were in the lower New Jersey Bayshore (denoted Delaware Basin 2, or DB2), which saw a decrease of 1,915 acres (3.08%; 775 hectares) and along the Upper Estuary (UE2, New Jersey) which saw a decrease of 414 acres (10.95%; 168 hectares). Estuarine wetlands in Delaware also experienced a large decline in downstream watersheds (LE2 and DB1; corroboration of findings in Tiner et al., 2011). Palustrine wetlands (tidal and nontidal) also saw a decline across the Estuary. Interestingly, there was one watershed area that experienced a net increase in tidal wetland extent between 1996 and 2010, which was the Lower Estuary watershed region in New Jersey (Table 5.2.2), which is discussed in Callout Box - 5.2.9. Another area of note is the PSEG restoration site on the west bank of the mouth of the Maurice River (Weishar, et al. 1998; Philipp, 2005), which may also be experiencing small increases in vegetated area. Although these small gains are good news and may reflect progress on restoring tidal wetlands, they are overshadowed by the ongoing cumulative losses of tidal wetlands throughout other areas of the Delaware Estuary. Figures 5.2.6 and 5.2.7 illustrate the trends for salt marsh (estuarine emergent) and palustrine (vegetated freshwater) wetlands from 1996 to 2010.

5.2.5 Mechanisms of Loss

There are many reasons why we continue to lose tidal wetlands in the Delaware Estuary. A recent examination of coastal wetland stressors (USEPA, 2015) cited a mix of deleterious practices such as mosquito control ditching, incremental filling, lack of regulatory oversight, regulatory loopholes for developers, shoreline hardening, hydrological alterations such as dredging, and pollution. These same stressors likely also contribute directly to wetland losses in the Delaware Estuary. In addition, increased rates of sea level rise and the spread of invasive species also contribute to the decline of coastal wetlands.

Riter and Kearney (2010) reported findings from satellite imagery, which suggested that marshes in the system are showing decreasing amounts of vegetative cover and increasing proportions of open water. Their effort updated the earlier study by Kearney et al. (2002) of both Chesapeake and Delaware Bays, which suggested that more than two-thirds of the salt marshes studied were in degraded condition, a sign of anticipated loss in the near future. Rapid shoreline erosion, measured at rates of up to 6 meters per year (Fig 5.2.8), also poses a significant threat to the sustainability of tidal wetland acreage in the Delaware Estuary. Plausibly, the erosion and loss of some wetlands might be helping to sustain others by subsidizing sediment supplies, but the net balance is still negative per year as determined by decreasing acreage, continued shoreline retreat, and lower overall vegetative cover.

The largest attribute of intertidal wetland loss is conversion to open water, which is the resulting effect of shoreline erosion and interior marsh drowning. Nationally, 96.4% of tidal wetland losses were due to conversion to open water, with about 3.5% attributable to human effects in the upland areas (Stedman and Dahl, 2008). Wetland loss from direct human influence is relatively small, but their impacts particularly on the quality of coastal ecosystems have undoubtedly been significant. Over 53% of the U.S. population lives in coastal counties, which make up only 17% of the land area of the conterminous U.S. (Crossett, et al., 2004). Development pressures and concomitant stresses on coastal systems are considerable and will likely increase. Since the advent of protections afforded by provisions in the 1972 Clean Water Act, direct loss of wetlands has slowed considerably; however, the effects of development still have detrimental impacts to estuarine environments. In the Delaware Estuary, human pressure by population growth, development, pollution, and/or land management will likely continue to have net negative effects on wetland acreage unless aggressive intervention strategies are implemented. These issues will also be exacerbated with

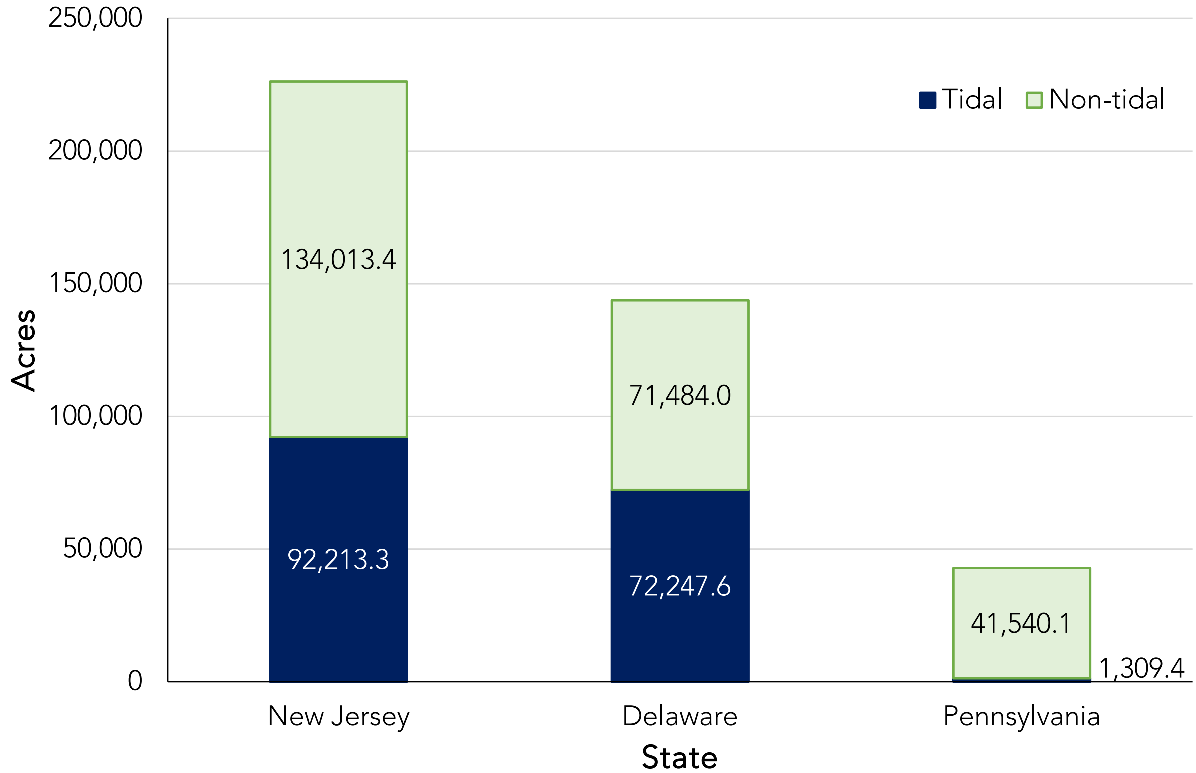

Figure 5.2.3 Proportion of tidal and nontidal wetlands by state in the Delaware Estuary (from NWI data).

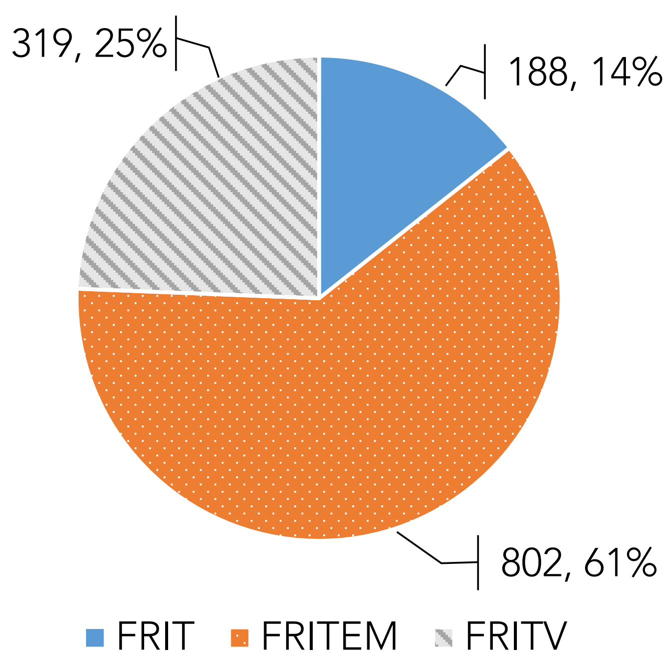

Figure 5.2.4 Proportion of the types of tidal wetlands in Pennsylvania, which are predominately freshwater. For descriptions of types, see Table 5B.1. Labels are acres, percent. These NWI data are as of 2015.

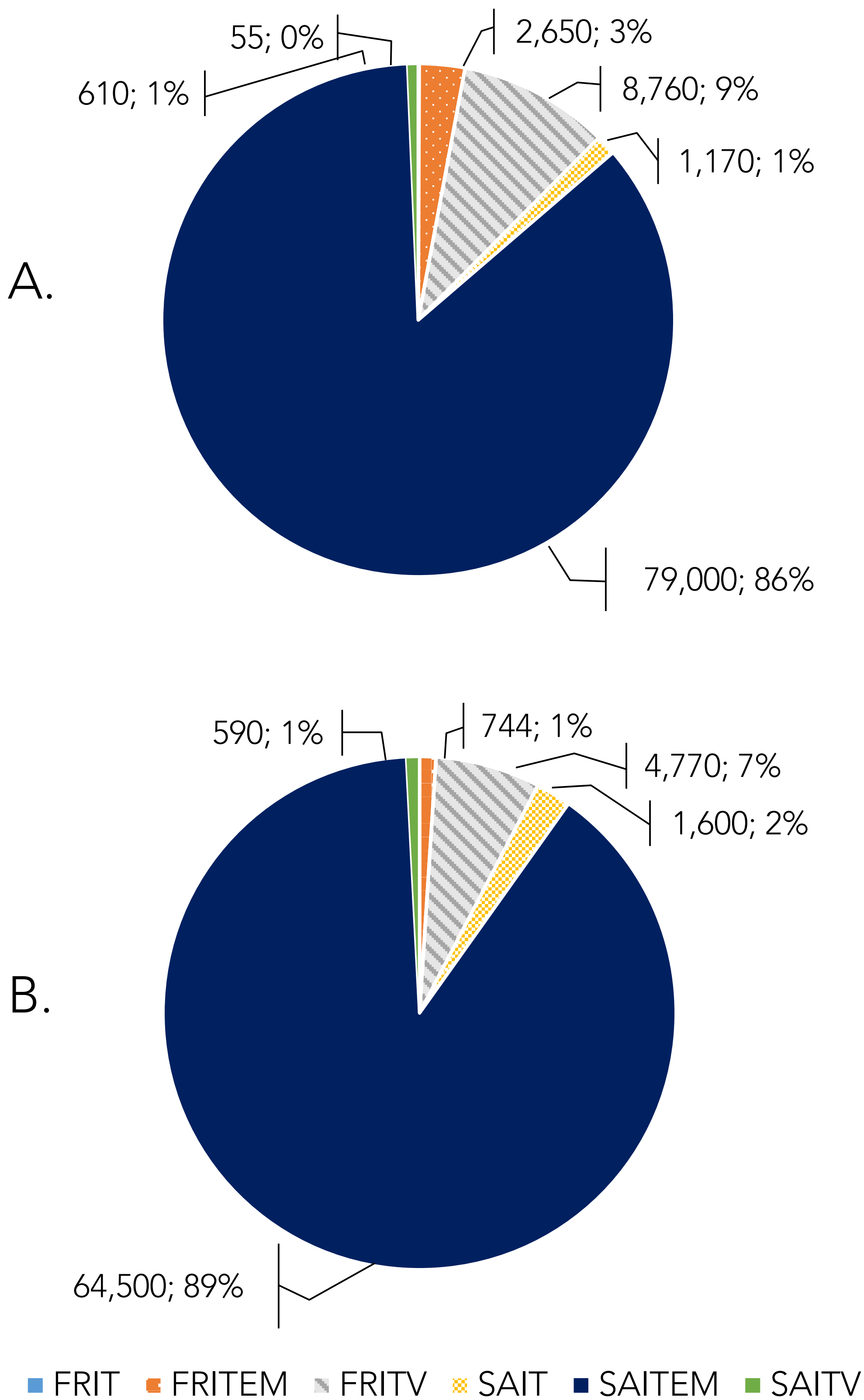

Figure 5.2.5 Proportion of the types of tidal wetlands in A) New Jersey and B) Delaware. These NWI data span the years of 1999-2002 in New Jersey and 2009 for Delaware. For description of types, see Table 5.2.1. Labels are acres, percent.

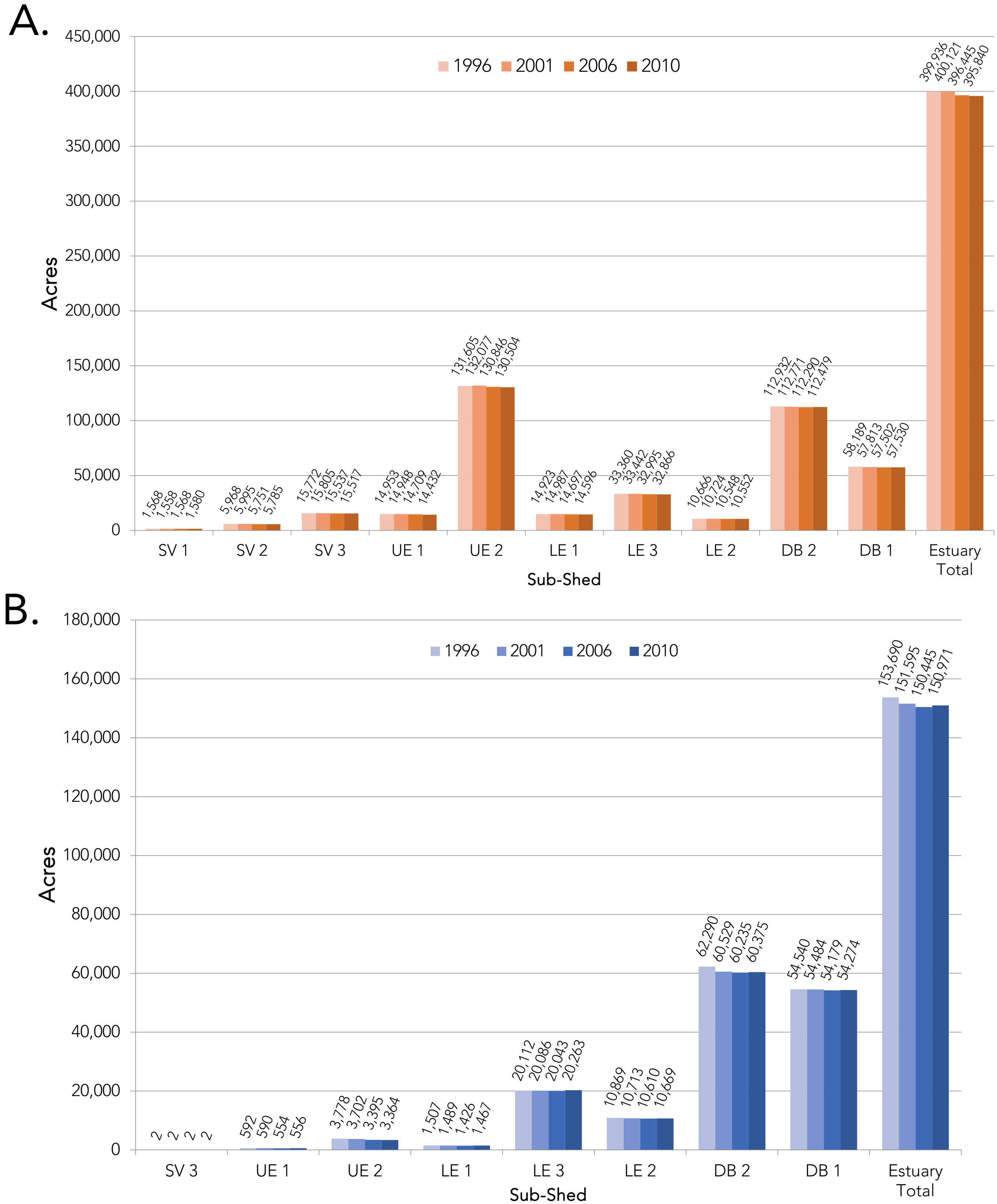

Figure 5.2.6 Total acreage of A) palustrine and B) estuarine wetlands in the Delaware Estuary by sub-shed (see Fig 5.2.2 for sub-shed locations) from 1996-2010.

Table 5.2.2 Change in palustrine and estuarine wetlands in the Delaware Estuary from 1996-2010 (see Fig 5.2.2 for sub-shed locations).

Sub-shed	Palustrine		Estuarine	
	Change (acres)	% Change	Change (acres)	% Change
SV 1	12.4	0.79%	0.0	0.00%
SV 2	-183.6	-3.08%	0.0	0.00%
SV 3	-255.5	-1.62%	-0.3	-14.74%
UE 1	-520.9	-3.48%	-35.2	-5.95%
UE 2	-1101.4	-0.84%	-413.9	-10.95%
LE 1	-327.7	-2.20%	-40.1	-2.66%
LE 3	-494.2	-1.48%	151.2	0.75%
LE 2	-114.1	-1.07%	-199.2	-1.83%
DB 2	-452.5	-0.40%	-1915.9	-3.08%
DB 1	-658.8	-1.13%	-265.2	-0.49%
TOTAL	-4096.2	-1.02%	-2718.7	-1.77%

climate change, so planning for negative, synergistic effects between sea level rise, storm frequency/intensity, and the human element will be crucial to sustaining coastal ecosystems.

A mechanism of regional concern is sediment management in the Delaware Estuary. Tidal marshes need ample sediment supplies to keep pace with sea level. The Delaware Estuary is a naturally muddy, wetland-rich system, but more sediments are removed each year through maintenance dredging than enter the system through surface runoff. Although there continues to be high suspended sediment loads in the water column and the overall budget (inputs and outputs) appears to be in balance (Walsh, 2011; Delaware Estuary Regional Sediment Management Plan, 2013), sediment studies suggest that the budget is currently subsidized by large inputs of sediments from eroding tidal wetlands. Tidal wetland loss through erosional forces is an ongoing and pervasive problem in the Delaware Estuary, especially in the Bay, where small coastal communities fight to keep their homes nearshore (e.g. Gandy's Beach; Fig 5.2.8). Organic sediments, like those derived from marshes themselves, may help sustain these systems now, but recent studies also suggest that mineral sediments, like those meant to be traveling downstream from the River, will become more important for marsh resilience with continuously increasing rates of sea level rise (Morris et al. 2016). Another regional concern is the effect of prolonged, high nutrient concentrations (Deegan et al. 2012; Turner et al. 2006). Salt marshes are naturally adapted for low nutrients; salt marsh grasses invest heavily in below ground production (i.e. roots and rhizomes) as a strategy for nutrient scavenging. Typically, this strategy contributes to peat accumulation and therefore elevation building with sea level rise. Nutrient loadings, however, may reduce below ground production, potentially impairing a marsh's ability to keep pace with sea level rise.

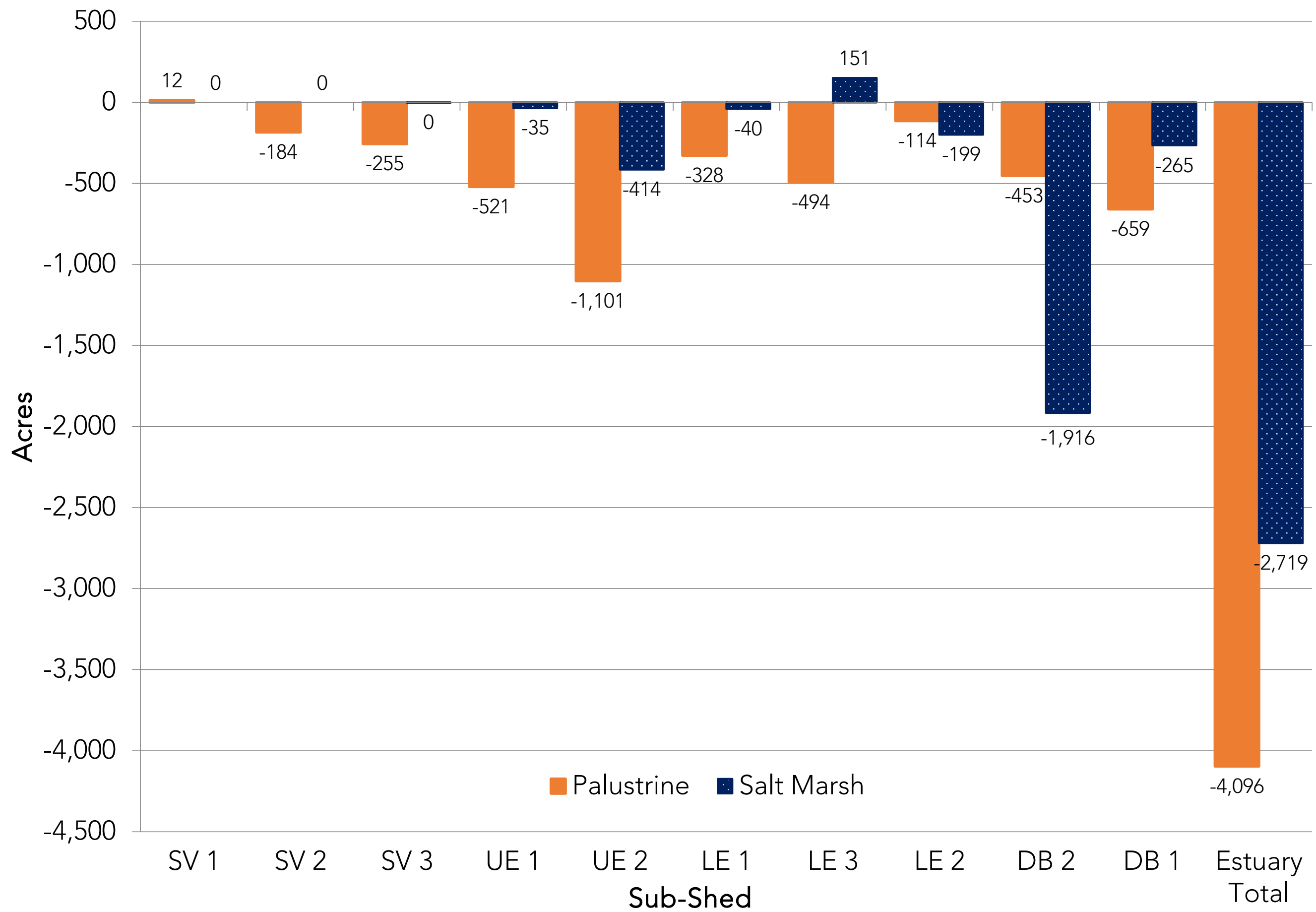

Figure 5.2.7 Total change of palustrine and estuarine wetlands in the Delaware Estuary by sub-shed (see Fig 5.2.2 for sub-shed locations) from 1996-2010.

5.2.6 Future Predictions

If the intensity and frequency of storms and associated tidal surges also increase with climate change, this could exacerbate the other threats and stressors discussed in Section 5.2.5. Warming trends are expected to boost the incidence of coastal storms, including nor'easters and hurricanes. On the other hand, a longer growing season and warmer temperatures are predicted to enhance primary productivity within smooth cordgrass dominated tidal wetlands (Kirwan, et al., 2009). A panel of wetland experts predicted, however, that the potential boost to primary production would be dwarfed by the threats posed by salinity intrusion and especially sea level rise (PDE, 2010). Moreover, all tidal wetlands face barriers to landward migration within the Delaware Estuary, most significantly in the Upper Estuary, which is more heavily urbanized (e.g. Wilmington, DE; Philadelphia, PA; Trenton, NJ). The potential for tidal wetlands to migrate landward is affected by habitat condition, slope, and degree of development. Areas that do not allow wetlands to easily migrate landward will need to accrete in place to preserve acreage (with little or no net shoreline loss) or subsequently drown.

By 2100 with a 1 meter rise is sea level, 119,000 acres (48,000 hectares) of irregularly flooded tidal wetlands were predicted to be lost based on model predictions from the Sea Level Affecting Marsh Model (SLAMM, V.6) (Kassakian, et al. 2017; Kreeger, et al. 2010). The loss of dry land and shrub-scrub habitat by migration was estimated to be 63,000 acres (25,500 hectares), but the conversion of marsh to open water was estimated to be 100,000 acres (40,000 hectares). Importantly, since no other habitat types rival tidal wetlands in productivity, the net loss of ecosystem services will be disproportionately large compared to acreage losses.

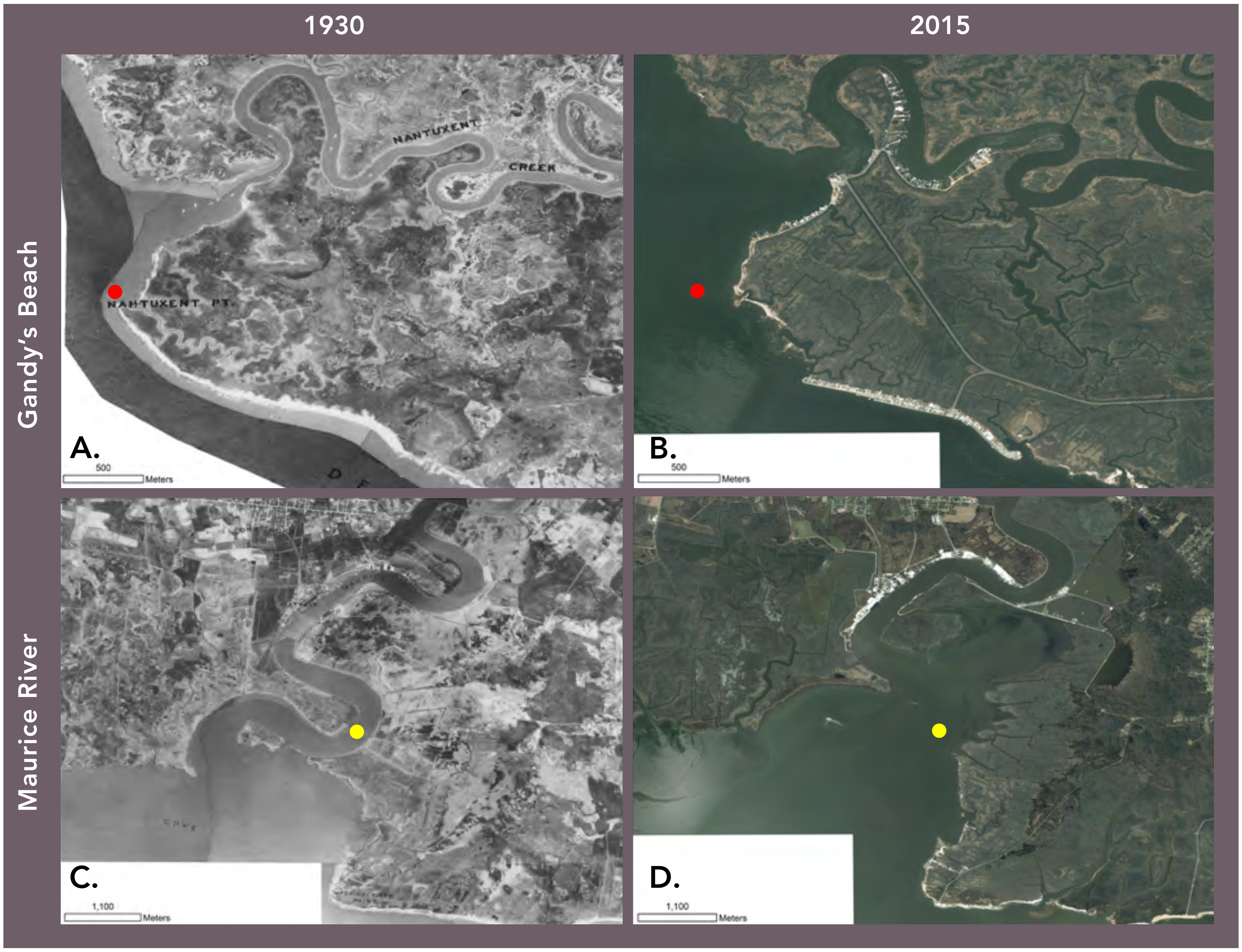

Figure 5.2.8 Aerial photographs of Gandy's Beach (A and B) and the mouth of the Maurice River (C and D). Left panes (A and C) are from 1930; right panes (B and D) are natural color images from 2015. Imagery courtesy of NJDEP's GIS web service. Red and yellow dots mark the same coordinates for Gandy's Beach and Maurice River, respectively.

The current rate of sea level rise in the Delaware Estuary is between 2.9-4.5 mm/year (0.11-0.18 in/year; NOAA Sea Level Rise Trends). This is in contrast to a long term average of ~1.8 mm/yr (0.074 in/yr)(4,000 year before present to about 1900; Engelhart and Horton, 2012). The last time the rate of sea level rise was as high as present was more than 4,000 years ago (Engelhart and Horton, 2012). Late Holocene reductions in sea level corresponded with the development of expansive tidal wetlands between 12 (at the mouth of the Bay) and 2 thousand years ago (upper Bay) in the Delaware Estuary (Fletcher et al., 1990). Lower rates of sea level rise are likely more conducive to tidal wetland development, as might be suggested from the late Holocene shift, but current sea level rise is beginning to accelerate towards more destructive rates.

In addition, the land of the Mid Atlantic is subsiding (sinking) from the collapse of a forebulge created by the glaciers more than 15,000 years ago; this process is called isostatic rebound (estimated at ~1.7 mm/yr in Delaware; Engelhart 2010). The effects of subsidence on sea levels are further compounded by changes in ocean currents (e.g. the Gulf Stream; Najjar 2010), which together result in greater rates of local relative sea level rise than global models predict. Intergovernmental Panel on Climate Change (IPCC) global sea level rise rates were calculated at 1.7 mm/yr (0.067 in/yr) between 1901-2010, but had increased to 3.2 mm/yr (0.13

in/yr) from 1993-2010 (Church et al. 2013). Globally, sea level is projected to rise, at the highest, ~0.74 m (2.4 ft) by 2100 (Church et al. 2013). In climate adaptation planning at the Partnership for the Delaware Estuary, 1.3 meters (4.3 ft) of relative sea level rise for every 1.0 meter (3.3 ft) of global sea level rise was estimated. For the 0.74 m (2.4 ft) expected globally, 0.96 m (3.1 ft) might be expected within the Delaware Estuary by 2100. Under the unlikely scenario of a linear increase, this would be ~11.6 mm/yr (0.46 in/yr).

The rate of relative sea level rise (RSLR) is critically important for determining the fate of tidal wetlands in the Delaware Estuary because of the tipping point that can be breached when the RSLR exceeds the rate at which marshes can build vertically. Many studies find that the suspended sediment load is intrinsically linked to the capacity of marshes to build vertically. The more suspended sediments within a tidal system, the better the capacity for building marsh with increasing rates of sea level rise. From long term monitoring of coastal marshes in the Delaware Estuary, most studied marshes have suspended sediment concentrations between 25-35 mg/L (Raper et al. 2016), suggesting tipping points to sea level rise may be between 10-20 mm/yr (D'Alpaos et al. 2011). If sea level increases exponentially through 2100, lower rates (4.5-6 mm/yr; 0.18-0.24 in/yr) in the next years would be followed by rates of larger magnitude in the latter half of this century (>12 mm/yr; 0.47 in/yr). A 2013 publication by Miller et al. suggested that coastal regions in the Mid Atlantic could potentially experience a 25 cm rise in sea level by 2030; if such projections are accurate, the sea level rise tipping point for marsh sustainability could be exceeded in the next 20 years. The immediate prognosis of tidal wetland extent in the Delaware Estuary will largely depend on the availability of sediments on which to build, but the longer term prognosis unfortunately suggests continued precipitous losses.

5.2.7 Actions and Needs

Sea level rise, salinity rise, development, outdated management paradigms, and pollutants are likely to continue to contribute to degradation and loss of tidal wetlands in the Delaware Estuary, unless very swift actions are taken to abate these impacts. The following are needed to aid efforts to reduce coastal wetland losses:

Proactive Adaptive Management Despite the dynamic nature of the coastline, many regulatory policies continue to treat the landscape as fixed in place. Restoration paradigms set goals based on historic conditions rather than future sustainability. It is generally still easier to obtain a permit for a bulkhead or other hard structure, which do not keep pace with sea level rise and contribute to degradation of tidal wetlands, than it is for a living shoreline. The state of Delaware had taken a lead in making living shoreline permitting and construction easier, and is now being followed by New Jersey and Pennsylvania. Ditching, diking, excavating, and filling of tidal wetlands still occur, often without a good understanding or monitoring of the consequences. To adapt to both climate change and continued watershed development, tidal wetland managers and landowners will need to adjust targets, expectations, and tactics to sustain the most tidal wetland habitat in the future.

In order to address the threats to the intertidal zone in the Delaware Estuary, an approach combining policy and regulatory remedies and actions on the ground is required. The Clean Water Act (1972), Coastal Zone Management Act (1972), and the Coastal Barriers Resources Act (1982), are evidence of the increasing importance of tidal wetlands in the policy and legal arena. Many states and counties have followed the lead of federal agencies and implemented their own regulations covering such wetland protection measures as buffer requirements, impervious cover limitations, and implementation of federal National Pollutant Discharge Elimination System (NPDES) and total daily maximum load (TMDL) guidelines. Continued promulgation and refinement of regulations and policies is a critical need, as demonstrated by the various emergency measures that are already underway or being called for in some Delaware and New Jersey areas (e.g. Prime Hook, Delaware; Gandy's Beach, New Jersey; Maurice Township, New Jersey) where tidal wetland losses are contributing to the decline of coastal communities. Given accelerating development and population pressures, as well as increases in relative sea level rise and climate change, these measures will need to be augmented just to maintain the current integrity of the intertidal zone. In particular, local differences in the extent of regulatory protection provided to wetlands poses a challenge to maintaining consistently high level of wetland quality and function throughout the Estuary.

Continued Monitoring and Scientific Study Another need for both managers and for future reporting is continued and complete monitoring data on tidal wetland status and trends, as well as scientific information on the causes of wetland loss and best management practices for averting such losses. Although monitoring efforts have been underway through MACWA efforts, the synthesis and continued support of these programs is paramount to understand the complex factors which impact coastal wetlands. These data will also be useful for prioritizing and planning intervention strategies across the Estuary.

Since the array of ecosystem services furnished by tidal wetlands scale with their condition, continued health assessments are also needed. Systematic watershed-level rapid assessments have been carried out for most of the tidal watersheds in Delaware, but there still are large gaps in surveys for New Jersey. Pennsylvania rapid assessments on tidal wetland condition were carried out in 2010. Changes to the urban corridor in the last seven years may have observable effects on tidal wetland condition, so these areas should be resurveyed to quantify these changes in tidal wetland condition. Vulnerability assessments which match site specific needs to appropriate intervention tactics, called Marsh Futures, has been spearheaded by the Partnership for the Delaware Estuary and partners. These methods can continue to be refined to address emerging needs of wetland managers. More scientific studies and restoration R&D pilot projects are also needed to strengthen current management and restoration practices to sustain greatest tidal wetland acreage cost effectively.

Investment in tidal marsh monitoring and science is difficult to fund at the multi-state scale of the Delaware Estuary. However, the benefits of tidal wetlands are beginning to be captured and capitalized (e.g. flood protection, nutrient and carbon capture, fish production), especially following Hurricane Sandy in 2012 when the protective function of coastal wetlands was confirmed. Tidal wetlands are already regarded as the most valuable natural lands. Managers should carefully consider how a projected loss of 25-75% of the tidal wetlands in the Delaware Estuary might affect coastal communities (lives and property) and regional economies (fisheries and shellfisheries, property values, nutrient criteria for industry). As markets for ecosystem services develop in the future, there could be increasing demand for essential information on trends in tidal wetland extent and condition, as well as tactics to protect and enhance tidal wetlands. However, until markets that can generate needed resources to sustain monitoring and assessment evolve, there will continue to be a need to collaborate and leverage funds to fill vital information gaps.

On-the-ground Action Efforts at preservation, both through regulatory and physical means, have had some beneficial impacts across the Estuary, but many areas are still undergoing degradation or conversion to open water. New active policies and tactics are needed to both facilitate the horizontal migration and vertical accretion of tidal wetlands. Given the rapid pace of change in tidal wetland extent and health, swift action to physically protect or enhance tidal wetlands is warranted to stem losses even if monitoring and scientific information are still developing. Marsh migration plans are needed and will require conflict resolution and education. Seaward protections and marsh enhancements can be just as difficult to implement due to permitting, logistical and funding challenges. However, there are efforts to explore beneficial use of sediments for enhancement (Delaware Estuary Regional Sediment Management 2013), develop new types of hybrid living shoreline tactics (Moody, et al. 2016; Fig 5.2.9), and craft estuary-wide strategies for intervention (e.g. Delaware Estuary Living Shoreline Initiative; Moody et al. 2017).

5.2.8 Summary

Tidal wetlands of the Delaware Estuary are some of the most productive habitats in the world, and they arguably represent the most ecologically and economically important type of natural habitat in the entire

Photo credit: Joshua Moody, Partnership for the Delaware Estuary

Photo credit: Joshua Moody, Partnership for the Delaware Estuary

Photo credit: LeeAnn Haaf, Partnership for the Delaware Estuary

Figure 5.2.9 Hybrid living shoreline concepts of DELSI: A) utilizing oyster shell bags to attenuate problematic boat wakes at Matts Landing, Maurice River, NJ; B) A mosaic of shell bags and oyster castles were installed to attenuate waves and provide substrate for oysters to improve water quality, at Nantuxent Creek, NJ; and C) Planting smooth cordgrass on coconut fiber logs (foreground), which were coupled with oyster castle pods (background) to expand the existing oyster reef footprint to improve water quality as well as attenuate waves at the Mispillion River Inlet, DE.

Delaware River Basin. By their very nature they are transient. They absorb tidal energy from the open marine environment and provide a buffer and sink for contaminants from upland areas. They also provide essential habitat for a wide range of organisms, as well as recreational opportunities for people. As long as the intertidal zone remains in a state of dynamic equilibrium, the benefits that they provide are maintained. However, when the processes which threaten the viability of the intertidal zone come to predominate over the processes which maintain equilibrium, this delicate ecosystem becomes imperiled. Current trends suggest that tidal wetlands, and hence the ecosystem services and direct financial and aesthetic benefits they provide, are being degraded and lost across all areas of the Delaware Estuary, especially salt marshes around Delaware Bay. Future projections suggest that these losses will increase, perhaps rapidly, likely resulting in a dramatic shift in the character and function of the Estuary ecosystem. More study and monitoring, along with proactive management and on-the-ground actions, are urgently needed to minimize ongoing losses since no type of replacement habitat will provide the same net level of ecosystem services that are currently furnished by these vital coastal wetlands.

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Suggested Citation for this Chapter

Haaf, L., D. Kreeger, A. Homsey. 2017. "Chapter 5.2 - Intertidal Wetlands" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 177-193.

5.2.9 Annual Variation of *Zizania aquatica*-dominated Marsh Extent: A case study of Mannington Meadows, Salem, New Jersey

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Introduction Amid prevailing decreasing trends of coastal wetland extent in the Delaware Estuary, CSC updates for 2010 showed an increase in acreage in Salem, New Jersey, or LE3. These coastal wetlands are brackish (2-8 ppt on average) and are a mosaic of marshes dominated by perennials (*Spartina alterniflora, Phragmites australis*) and the annual *Zizania aquatica* or Annual Wildrice (AWR; Fig 5.2.9.1). As AWR typically occupies fresher systems, the Salem River marshes are likely the farthest downstream stands along the Delaware River's estuarine gradient. The unique floral composition of these marshes called into question potential discrepancies in the CSC analyses, given that AWR is short lived compared to other plants (germination to senescence is May-August, peak growth ~July). To test if these marshes had indeed undergone expansion, despite continued loss in other areas, additional Landsat imagery analyses were carried out within the window of maximum AWR extent.

Figure 5.2.9.1 Panicle (seedhead) of annual wild rice. Photo by LeeAnn Haaf.

Methods Landsat scenes with <20% cloud cover were selected from July to early August (a 47 day period) to capture extent of AWR (Earthexplorer.usgs.gov; resolution is 30x30 m). Years chosen were 1995, 1996, 2006, 2007, 2010, and 2016. Each scene was clipped to the study area (Fig 5.2.9.2) and the ArcMap Image Classification tool bar (Spatial Analyst) was used to perform supervised classification of marsh extent (no differentiation of vegetation type). Sea level (SL) anomaly data (NOAA station Reedy Point, DE ID#8551910) were obtained and averaged for seasonal and annual anomalies. Seasonal periods included concurrent winter, spring, and summer, as well as the previous year fall and summer. Spearman's rank correlation statistic was performed to evaluate correlation between SL anomalies, Julian day, and marsh extent. A linear regression was run on marsh extent. Standard errors were calculated for SL anomalies. SL rose at 3.45±0.51 mm/yr at the tidal station, regardless of anomalies observed.

Figure 5.2.9.2 Aerial photograph (2015) of the Mannington Meadows marsh complex study area (grey outline), in Salem, NJ.

Results Marsh extent correlated positively (p=0.019; rho = 0.8857) with SL anomalies in the previous year's autumn months (Aug.-Oct.; Fig 5.2.9.3). No significance was found for other SL anomalies averages (p>0.05); these correlations, despite non-significance, were generally negative, whereas the fall SL variation was positive. There was no significant correlation with Julian day (rho = 0.6, p=0.208). It should be noted that despite this, 47 days is over a third of the plant's life cycle and the day of image capture could affect results of other analyses. Regression results were not significant (p=0.64). Average marsh extent was 400 ± 38 hectares (± 95% CI; Fig 5.2.9.4).

Discussion Extent of the marsh in this study increased on average from 1996-2016 by 84 hectares (~207 acres); intra-annual variation, however, was high (±38 hectares or ~94 acres) and perhaps driven by fall sea level variations of the previous year. CSC reports from 1996-2010 suggested that 61 hectares (151 acres) of estuarine wetlands had developed in LE3. These additional analyses corroborated this increase.

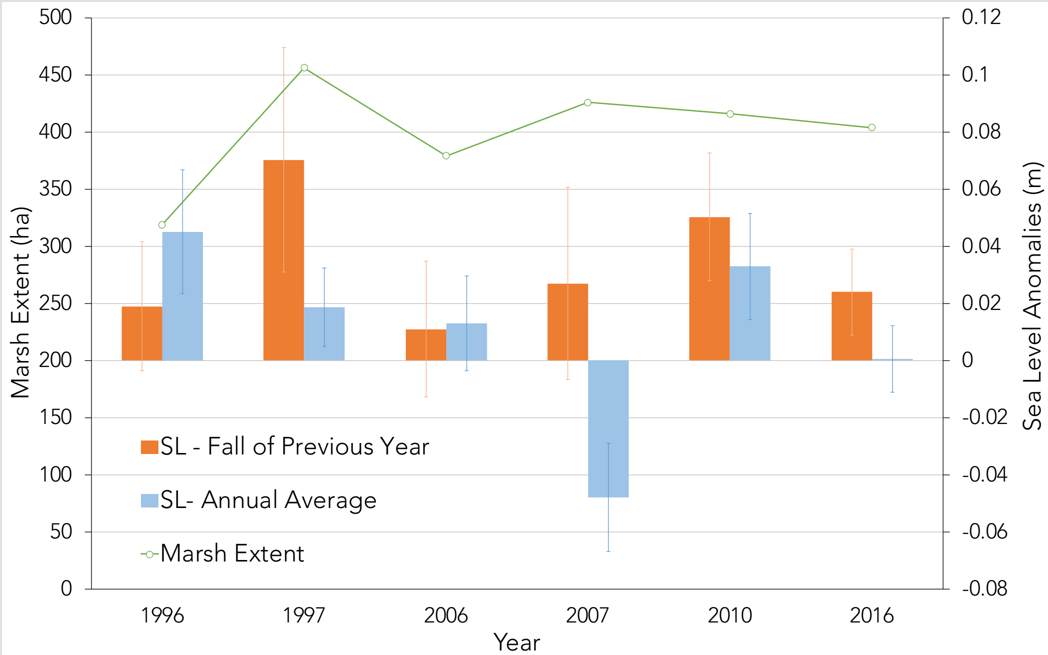

Figure 5.2.9.3 Change in marsh extent (green line, right axis) and sea level (SL) anomalies (left axis). Error bars are standard error (N=3 and 12, for fall and annual, respectively). Only fall anomalies were significantly correlated with marsh extent.

Landscape analyses taken at 5 year intervals or more, like CSC, may misrepresent net AWR- dominated wetland extent changes due to high year-to-year variability and intra-annual dependence. These fluctuations may become attenuated, however, by the invasion of perennial *Phragmites australis*, or salinity-driven shifts to the more salt tolerant, and perennial, *S. alterniflora*.

In conclusion, 2010 marsh extent was greater than in 1996, but high variability from year-to-year suggest that robust long term trends require more temporal resolution. For instance, if 1996 was excluded, the trend would suggest a net decrease in extent from 1997 to 2016. In the future, trend analyses should seek to address these needs and perform additional imagery analyses focusing on tidal wetlands dominated by annual species. Annual species' sensitivity to certain environmental parameters would yield important information about ecological relationships under changing conditions and about estuarine health over time.

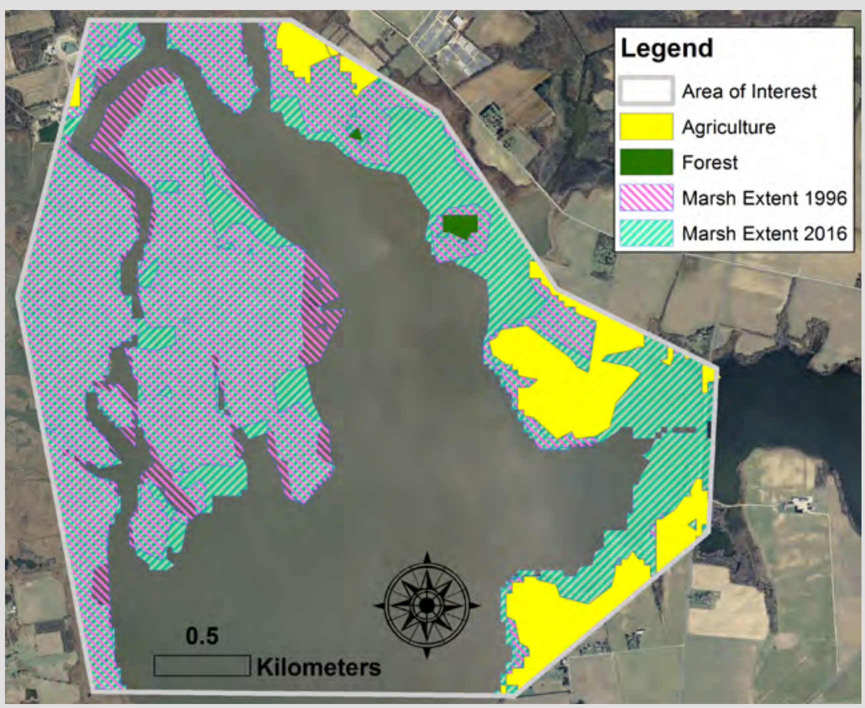

Figure 5.2.9.4 Image classification results of marsh extent.

5.3 Nontidal Habitats

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1. Delaware River Basin Commission; 2. The Nature Conservancy, New Jersey; 3. The Nature Conservancy, Pennsylvania

Reprinted from Partnership for the Delaware Estuary. 2012. Technical Report for the Delaware Estuary and Basin. P. Cole, A. Padeletti, D. Kreeger (eds). PDE Report No. 12-01. 255 pages.

5.3.1 Freshwater Wetland Acreage

5.3.1.1 Introduction

Nontidal wetlands, including forested and shrub swamps, bogs, fens, vernal pools, and riverine wetlands, provide habitat for a diverse array of terrestrial, aquatic, amphibian, and bird species (Davis 1993, Mitsch and Gosselink 2000, Faber-Langendoen et al 2008). Wetlands also serve many hydrologic, biogeochemical, and habitat functions, which are strongly influenced by watershed position (Brinson et al. 1995). Headwater wetlands retain and store precipitation, recharging groundwater resources. They are important sources of water and organic and inorganic materials that support downstream aquatic systems. Riverine and floodplain wetlands can store overbank flows, dissipate energy, provide a local supply of large woody debris, and both supply and retain coarse particulate organic matter. Wetland size, density, and landscape context, including condition of adjacent lands and connectivity among riverine, wetland, and upland habitats, are important indicators of condition. Large wetlands are critical for maintaining suitable habitat for many of the priority species within the state wildlife conservation plans. For example, the Pennsylvania Comprehensive Wildlife Conservation Strategy (CWCS) emphasizes that conservation of large wetland habitat is especially critical for wildlife conservation (PGC and PFBC 2005). While the CWCS definition of "large wetlands" depends on the wetland type and species of concern, it typically defines large wetlands as between 12 and 100 acres (5 and 40 ha) (or larger).

Separating nontidal wetlands highlights the value and significance of these systems, which have experienced significant losses in the Basin. For example, in the state of Delaware more wetlands were lost between 1992 and 2007 than in the previous 10 years; approximately 99 percent of those losses were to nontidal/freshwater wetlands (Environmental Law Institute 2010).

5.3.1.2 Description of Indicator

Headwater wetland area and the number of large contiguous headwater wetlands (greater than 100 acres/ 40 ha) were calculated for each sub-basin within the Delaware River Basin. Together, these serve as potential indicators of the degree to which wetlands are providing critical functions in headwater regions, including recharging groundwater and storing and releasing water and organic and inorganic materials to support downstream aquatic systems.

Nontidal wetlands were defined by first selecting the woody and emergent wetland land cover classes from the National Land Cover Dataset (NLCD

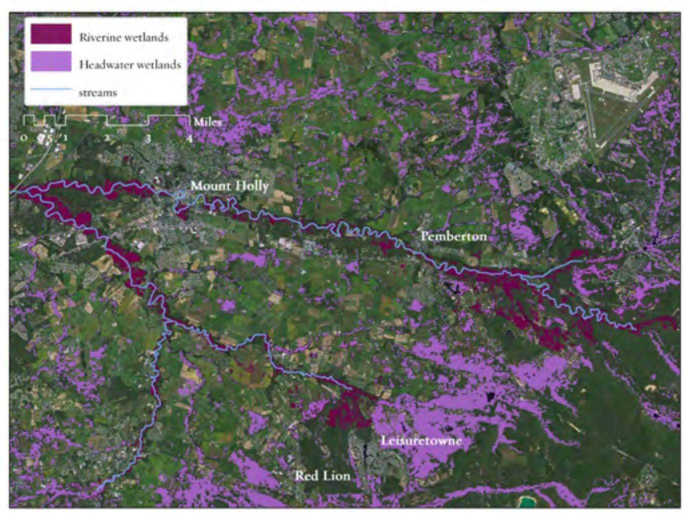

Figure 5.3.1 Riverine and headwater wetlands within the Rancocas Creek watershed, New Jersey.

2001). Open water features such as ponds, lakes, and reservoirs were not included. Nontidal wetlands were then classified according to the National Vegetation Classification System (NVCS) (Westervelt et al. 2006) and further separated into headwater and riverine wetlands (Fig 5.3.1). Riverine wetlands were associated with the floodplains of rivers with drainage areas greater than approximately 40 square miles (10,359 ha). Headwater wetlands exist along the riparian corridors of streams with drainage areas less than approximately 40 square miles (10,359 ha).

Within headwaters, contiguous headwater wetlands were defined as areas with connected wetland landcover (i.e., woody or emergent wetland pixels that are connected on a side or on the diagonal). These contiguous wetlands potentially include multiple wetland types according to various existing classifications, but the overall size is one indicator of potential wetland function. The total area of each contiguous headwater wetland was calculated.

5.3.1.3 Present Status

Figure 5.3.2 illustrates the total headwater wetland area and the number of contiguous headwater wetlands larger than 100 acres (40 ha) within each sub-basin. Despite wetland losses, the Delaware River watershed has several sub-basins with abundant headwater wetlands. Noteworthy concentrations are located in the Upper Central and Lehigh Valley sub-basins and on the coastal plain within Upper and Lower Estuary and Delaware Bay sub-basins.

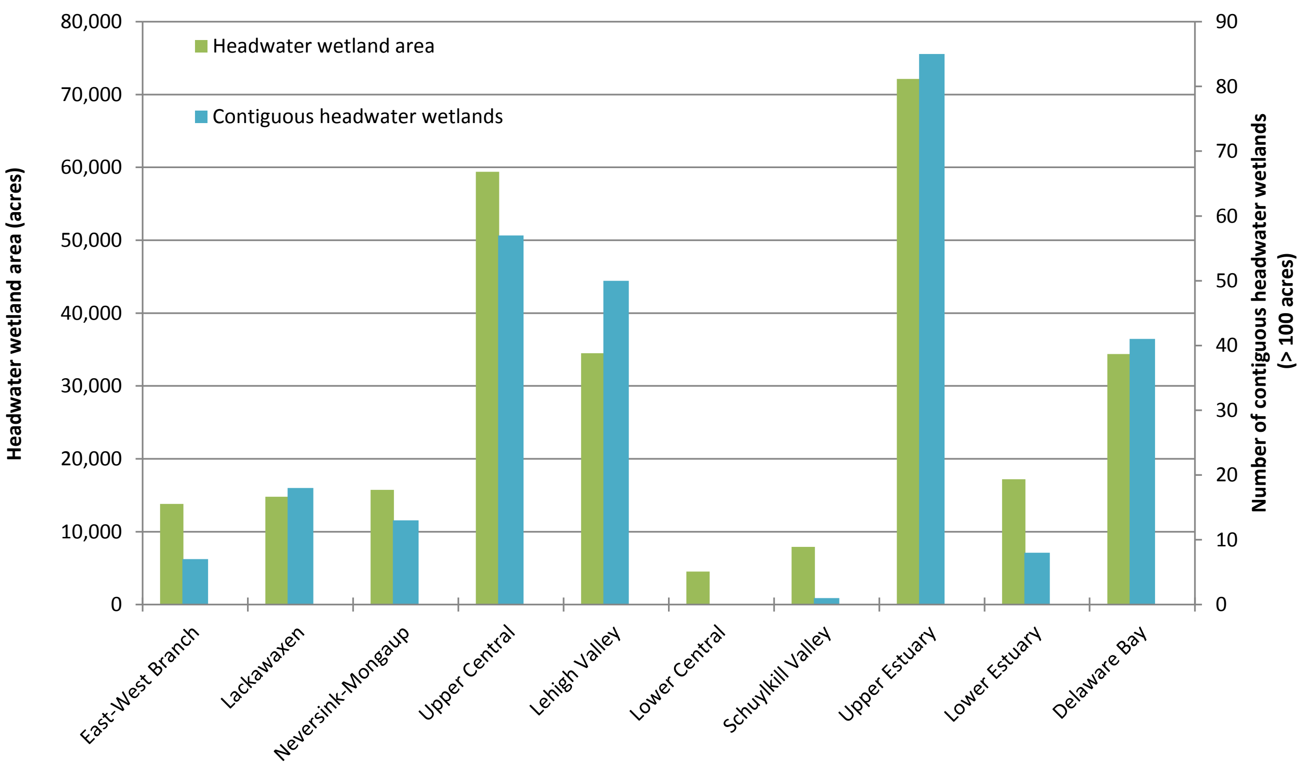

Figure 5.3.2 Total headwater wetland area ranges from approximately 4,500 acres (1821 ha) in the Lower Central sub-basin to over 72,000 acres (29,137 ha) in the Upper Estuary sub-basin. The Upper Estuary sub-basin also has 85 headwater wetlands that are larger than 100 acres (40 ha). This is the highest number of any sub-basin in the Delaware River watershed.

Both the Upper Central and Lehigh Valley sub-basins contain at least 50 headwater wetlands that are larger than 100 acres (40 ha). These sub-basins also overlap with the glaciated portions of the Pocono Plateau, which includes the greatest diversity of wetlands in the state of Pennsylvania (Davis 1993). Boreal conifer swamps, oligotrophic kettlehole bogs, cranberry and bog-rosemary peatlands, and acidic broadleaf swamps occur throughout the region. Other unique wetland communities are found along the limestone valley, where mineral-rich groundwater supports calcareous fens, seepage swamps, and limestone wetlands. Cherry Valley National Wildlife Refuge and the Mt. Bethel Fens in Pennsylvania and the Johnsonburg and Sussex Swamps in New Jersey contain examples of these systems. Vernal pools are also scattered throughout the region, with concentrations along the toe slopes of the Kittatinny Ridge.

Although the Upper Estuary sub-basin includes Trenton and Camden, NJ, Philadelphia, Pennsylvania, and other urban and suburban areas, this watershed contains over 70,000 acres (28,322 ha) of nontidal wetlands and 85 wetlands larger than 100 acres. These headwater wetlands are especially abundant on the coastal plain in New Jersey, including along Crosswicks Creek and the North and South Branch Rancocas Creek.

5.3.1.4 Past Trends

Wetlands slow down, capture and cleanse rainwater before releasing it to rivers, oceans, lakes and groundwater. They shelter wildlife and provide breeding and spawning grounds for commercial and recreational fisheries. They store stormwater, releasing it slowly to help prevent floods, and support recreational activities.

Yet for much of our history, wetlands have been undervalued. By the mid-1980s half the wetlands in the continental U.S. had disappeared, with losses averaging 500,000 acres (202,343 ha) per year. Regulations to control wetlands loss existed, but were often slow, unpredictable, expensive and frustrating for land owners.

In the summer of 1987, at the request of Lee Thomas, Administrator of the U.S. Environmental Protection Agency, The Conservation Foundation convened the National Wetlands Policy Forum, chaired by Governor Thomas H. Kean of New Jersey, to address major (32,374 ha) policy concerns about how the nation should protect and manage its valuable wetlands resources.

The goal of the Forum was to develop sound, broadly supported recommendations on how federal, state and local wetlands policy could be improved. In late 1988, the Forum published its final report, a 70-page consensus document that presented approximately 100 recommendations on a variety of issues including promoting private stewardship, improving regulatory programs, establishing government leadership and providing better information. Among the key recommendations was that national policy be guided by a goal of “no overall net loss” of the nation’s remaining wetlands and, over the long term, to increase the quantity and quality of the nation’s wetlands resources.

This goal has guided national wetlands regulatory and non-regulatory programs and policy ever since.

In the years since the Wetlands Forum, the rate of wetlands loss in the U.S. has slowed dramatically to the point where achieving the goal of “no net loss” may be in sight. This is truly a remarkable accomplishment.

Private land owners have made a major contribution, in recent years enrolling an average of 200,000 acres per year in the national Wetlands Reserve Program, one of the programs recommended by the Forum. Total acreage in the program now exceeds a million acres.

Federal and state agencies stepped up and provided increased leadership in numerous ways and in every Administration since the Forum’s recommendations, improving regulatory programs and providing better information. Shortly after the Forum’s report, USEPA and the Army Corps signed a Memorandum of Understanding to better coordinate regulatory programs, reducing confusion for landowners.

5.3.1.5 Future Predictions

While filling and conversion of wetlands for agricultural and urban development has generally decreased over time, different stressors in the form of new industrial development seeking a location in small headwater watersheds will have to be carefully managed. In addition, it is likely the precipitation patterns of the next 100 years will be more extreme than the past, resulting in changing water budgets at a watershed scale and even greater ecosystem service values attributed to freshwater wetlands in the future.

5.3.1.6 Actions and Needs

Many positive actions are underway and require continued vigilance by Basin management community:

1. Continued attention to quantifying ecosystem service values.
2. Continued attention to harmonizing state and federal regulatory programs.
3. Continued attention to funding conservation initiatives and wetland reserve programs.
4. Continued effort to quantify feedback loops like the United States Department of Agriculture (USDA) Conservation Effects Assessment Program.
5. Passage of the Delaware River Basin Conservation Act of 2011 - championed by Senators Carper and Coons of Delaware, Senator Schumer and Gillibrand of New York, and Senators Menendez and Lautenberg of New Jersey-- which would establish a federal program at the U.S. Fish and Wildlife Service to coordinate voluntary restoration efforts throughout the Delaware River watershed.

5.3.2 Riparian Corridor Condition

5.3.2.1 Introduction

Natural riparian corridors are important for stream and river health because they support physical and ecological processes and provide habitat corridors for river-associated birds and mammals. Depending on position within the watershed, riparian corridors play various functions. In headwater areas, hydrology, sediment input, and channel network formation is largely influenced by riparian corridors. Further downstream, riparian corridors often include well-developed floodplains, which may or may not be confined within steep valley walls. Floodplain condition affects channel and bank stability, water quality, sediment storage, and water storage during overbank flows. Riparian condition is one indicator of headwater and floodplain functions throughout a watershed.

5.3.2.2 Description of Indicator

The active river area model and land cover data were used to assess riparian corridor condition throughout the nontidal portion of the Delaware River Basin. The active river area framework is a spatially-explicit approach to identifying the areas within a watershed that accommodate the physical and ecological processes associated with river systems (Smith et al. 2008). The spatial model includes three primary components within the riparian corridor: floodplains, riverine wetlands, and riparian areas that are likely to contribute woody debris, coarse particulate organic matter, sediment, and energy to the riverine system. The area and percent of natural land cover (predominately forest and wetland land cover) for headwater riparian corridors (i.e., all streams with drainage areas less than approximately 40 square miles/10,359 ha) was calculated. The area and percent of natural cover within floodplains (i.e., all streams and rivers with drainage areas greater than 40 square miles/10,359 ha) for each major sub-basin was calculated. Comparing riparian condition in headwaters and floodplains is one indicator that reveals how ecological processes may have been altered in various subwatersheds throughout the nontidal portion of the Basin.

5.3.2.3 Present Status

In the Upper and Central Regions of the Delaware River Basin, the majority of riparian corridors are at or above 70% natural cover, both in headwaters and in floodplains (Fig 5.3.3). The riparian corridors in the Neversink-Mongaup sub-basin are in best overall condition compared to any other sub-basin; over 90% of the riparian corridors are in natural cover, both within headwaters and floodplains of larger rivers (Fig 5.3.4). Natural riparian corridors in the headwaters, such as those in the Upper Lehigh River and Tobyhanna Creek watersheds, are essential for maintaining water quality and quantity for downstream ecosystems and water users (Fig 5.3.5). In the Lower Region, riparian corridors are much more developed, although there are still some large areas of natural cover within floodplain riparian corridors in the Schuylkill and Lower Central Sub-basins. For example, the floodplain areas along the main-stem between Allentown, PA and Trenton, NJ, are approximately 78% forest and wetland cover. This area includes the Lower Delaware Wild and Scenic River, which is part of the National Wild and Scenic River system managed by the National Park Service.

5.3.2.4 Past Trends

Riparian corridors (floodplains, riverine wetlands and riparian areas) have long been recognized as environmentally sensitive, ecologically diverse, and hydrologically important areas within a watershed.

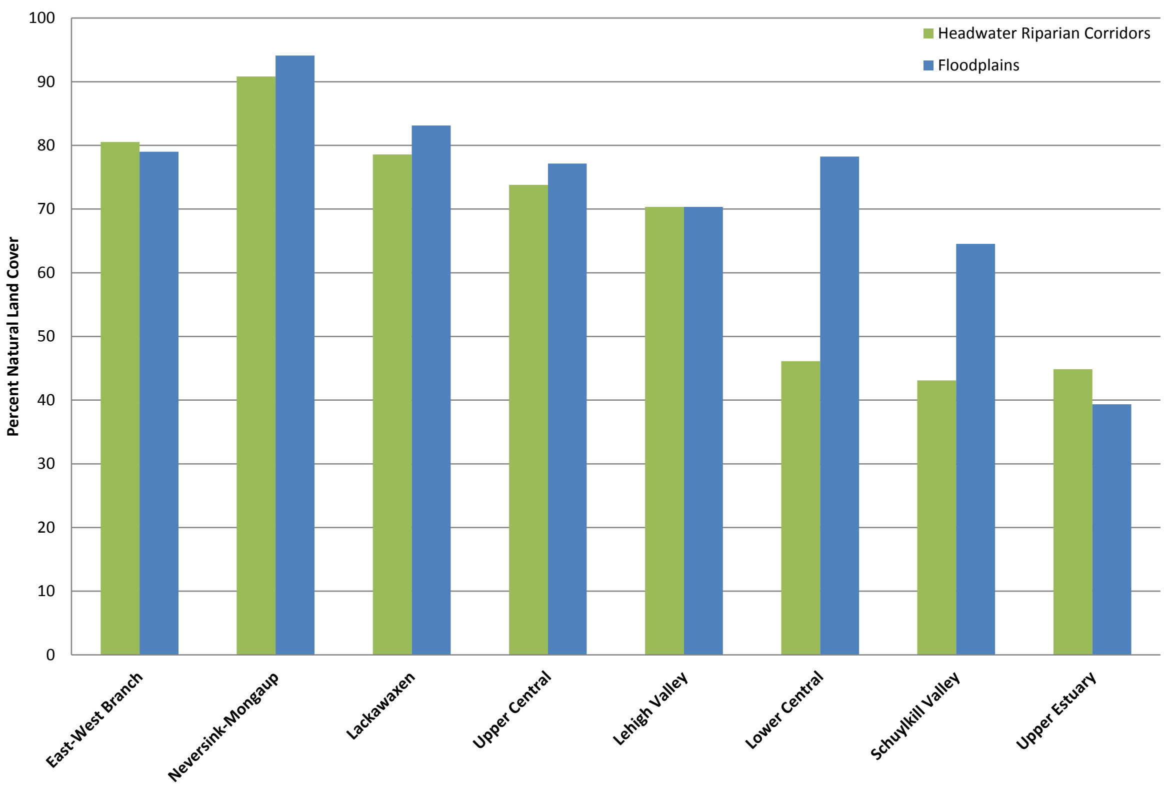

Figure 5.3.3 Headwater and floodplain riparian condition with Delaware River sub-basins. The majority of floodplain and headwater riparian corridors in the Upper and Central Regions of the Delaware Basin contain at least 70% natural cover. Although percent natural cover is lower in the nontidal portion of the Lower Region, there are still floodplain areas with extensive natural cover, including the portions of the Schuylkill Valley and mainstem Delaware between Allentown, PA, and Trenton, NJ (Lower Central sub-basin).

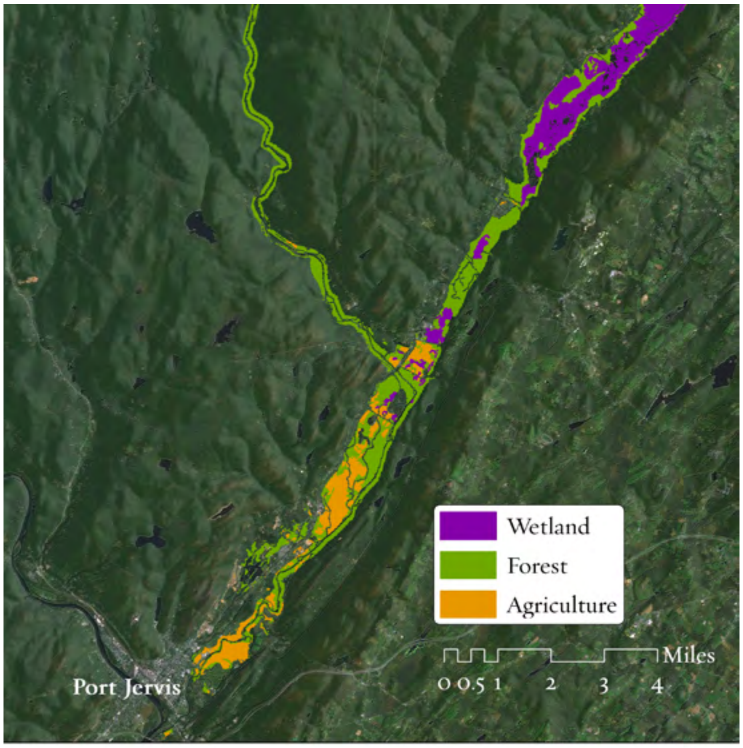

Figure 5.3.4 In the Neversink-Mongaup sub-basin, approximately 94% of the floodplain area is in forest or wetland land cover.

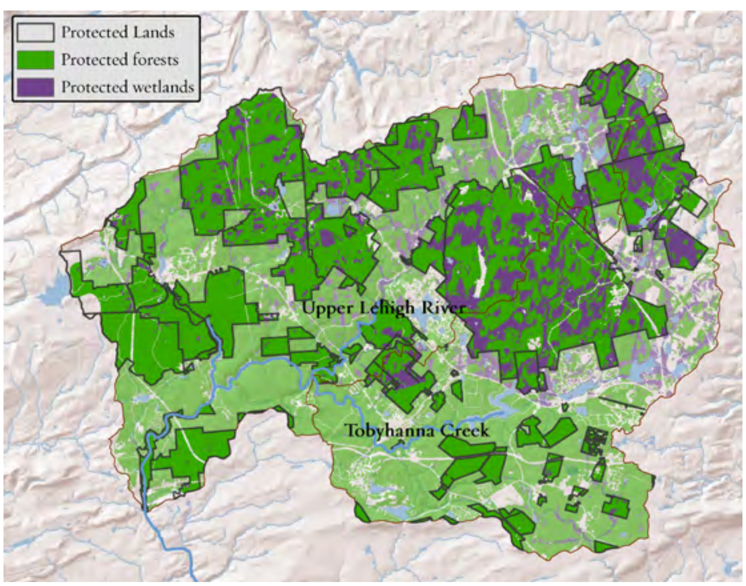

Figure 5.3.5 Headwaters within the upper Lehigh Valley sub-basin include extensive forests and wetlands within the riparian corridors. Much of this area is also in protected lands.

Even though the natural functions of these corridors and the hazards associated with their occupancy are widely known, people have always been attracted to water. Historically, settlements have arisen along waterways because they contain natural features beneficial to human societies (fertile soil, transportation links, water supply, hydropower, and aesthetic beauty). One consequence of human development of riparian corridors is the physical alterations of both stream channels (dams, levee construction, straightening, and dredging) and the floodplain landscape, impacting not only the integrity of the watercourse, but also resulting in significant social and economic consequences. Floods in developed floodplains devastate families, businesses, and communities, and cause more damage to life and property than any other natural hazard. These problems exist in many parts of the country, but the riparian corridor condition of the Delaware River Basin is relatively good. As noted above, riparian corridors associated with headwater watersheds and floodplains in the Upper Basin enjoy 70% or more natural cover. Similarly, riparian corridor condition associated with the Central Basin Delaware River floodplain has plentiful forest and wetland cover. The national status of the Delaware as the largest free flowing river East of the Mississippi, coupled with high water quality directly attributable to riparian corridor condition have led to inclusion of three-quarters of the nontidal Delaware River (about 150 miles) in the National Wild and Scenic Rivers System. In contrast, only one quarter of one percent (11, 000 miles) of the 3.5 million miles of rivers in the nation has been included in the System.

5.3.2.5 Future Predictions

In 2004, the four Basin Governors and federal agency Regional Executives signed a forward looking Basin Plan that identified five Key Result Areas, one of which focused on Waterway Corridor Management. Specifically, the Plan specified a Desired

Result involving: waterway corridors that function to minimize flood-induced loss of life, protect property and floodplain ecology, preserve channel stability, provide recreational access, and support healthy aquatic and riparian ecosystems. Work is now underway by many partners to implement the specific goals and objectives enumerated in the plan, including an annual report out of progress at the fall Delaware River Basin Commission meeting. Another significant milestone in 2011 was realized with the completion of the "Delaware River Basin Priority Conservation Areas and Recommended Conservation Strategies" Report. The report was developed by The Nature Conservancy, Partnership for the Delaware Estuary, and Natural Lands Trust, and funded by the National Fish and Wildlife Foundation. It focuses on Floodplains, Headwaters and Nontidal Wetlands and provides a platform for shared conservation and restoration priorities across the Basin.

5.3.2.6 Actions and Needs

The Water Resources Plan for the Delaware River Basin (Basin Plan) Objective 2.3 D called for "Implementing Strategies to protect critical riparian and aquatic habitat" and established milestones for identifying, mapping and prioritizing critical habitats. It also called for development and adoption of protection and restoration strategies.

1. Action: The Final Report for the National Fish and Wildlife Foundation titled "Delaware River Basin Priority Conservation Areas and Recommended Conservation Strategies" was completed in 2011. The report includes detailed maps by sub-basin showing watershed specific freshwater system priorities. For example, the Upper Delaware River Basin is divided into 22 watersheds and place-specific conservation strategies (Headwater Networks; Floodplain Complexes; Headwater Wetlands; and Riverine Wetlands) are identified and prioritized.

2. Action: The Conservation Plan referenced in Item #1 functions as vehicle for collaborative restoration and protection action.

3. Action: The Conservation Plan also serves as preliminary set of targets for implementation of the Delaware River Basin Conservation Act of 2011, if it is successful in becoming federal law.

4. Need: The Basin conservation community needs to work with its Congressional Delegation to continue to advocate for passage of the Delaware River Basin Conservation Act.

5. Action: The Delaware River Basin Commission Flood Advisory Committee conducted a careful assessment of Floodplain Regulations both in the Basin and around the country in 2008 and 2009. In October 2009, they presented a report containing twelve recommendations for more effective floodplain regulations to the Commission. The Committee determined that minimum floodplain regulations, administered by FEMA through the National Flood Insurance Program, do not adequately identify risk or prevent harm. They also found that floodplain regulations are inconsistent from State to State and from community to community. They recommended that floodplain regulations need to be applied more consistently and comprehensively, on a watershed basis that reaches across jurisdictional boundaries.

6. Need: DRBC needs to work with FEMA to advance their Risk Mapping, Assessment and Planning (Risk MAP) strategy to work with local officials to use flood risk data and tools to effectively communicate risk to citizens and better protect their citizens. The DRBC Flood Advisory Committee recommendations could be one component of the FEMA strategy to work with communities at a watershed scale to make the Basin more flood resilient.

5.3.3 Fish Passage

5.3.3.1 Introduction

The Delaware River lacks any dams on its main-stem that block passage of fish, a feature which is remarkable for a river of its size. Diadromous fish like American Shad, Alewife, Blueback Herring, Striped Bass, Sea Lamprey, and American Eel can travel over 300 miles (483 km) from the mouth of the river up to its origin (and back out to the ocean) without being blocked by a barrier. Unobstructed stream habitat like this is critical for migratory fish, especially for anadromous fish to be able to access freshwater spawning grounds. Long stretches of connected streams also are important for local movement of resident fish and other aquatic organisms. Some resident species, such as the tessellated darter, also serve as host fish for certain freshwater mussels. Consequently, the ability of fish like this one to move within a stream system is also critical for freshwater mussels, which rely on host fish to disperse their young and colonize new habitats.

Unlike the main-stem, most tributaries of the Delaware River have been dammed over time. Over 1,400 dams within the Basin are tracked by various federal and state agencies; additionally, many smaller, unregulated dams that are not captured by these databases exist in the Basin. While large dams pose clear barriers to fish passage, small run-of-river dams and even inadequate culverts can impede fish passage. Cumulative effects of barriers can dramatically reduce the amount of accessible habitat for fish within a stream network, although the first few barriers in a stream network have the greatest impact on connected habitat (Cote et al. 2009).

5.3.3.2 Description of Indicator

Using dams in state and Army Corps of Engineers (National Inventory of Dams) databases, as well as a small number of hand-mapped blockages in the Delaware Bay coastal area, we identified the length of each connected stretch of a river network (i.e., portions that have no dams occurring within that stretch) using the Barrier Analysis Tool (BAT, v.1). This tool calculates the total length of a connected stream network by adding the lengths of a river and all connected tributaries between barriers (or between a river origin and the first barrier downstream, or the river mouth and the first barrier upstream). Results of the analysis highlight the longest connected river networks, including those that have no blockages from their headwaters downstream to the Delaware River and out to the Bay.

It is important to note that our analysis included dams that have fish ladders installed on them. These dams were not removed from the analysis primarily because many fishways still pose barriers to fish passage; while they may allow for effective passage of a handful of species similar to those for which they were designed, many fish are still unable to use fish ladders effectively, if at all. Perched, undersized or blocked culverts also can be significant barriers to fish movement; however, this type of barrier was not included in our analysis, due to a lack of a basin-wide culvert dataset.

5.3.3.3 Present Status

The Delaware River is distinguished by being the longest free-flowing river in the eastern United States. Anadromous and catadromous fish species can travel unimpeded through over 500 miles (802 km) of connected rivers and streams, from the mouth of the Delaware River upstream to Hancock, New York and as far upstream on any connected tributary as the first barrier (Fig 5.3.6). Many tributaries lack dams in their downstream portions and thus allow migratory fish like river herring to access spawning habitat downstream of any barrier. For example, the Rancocas, Flatbrook, and Neversink River systems all have significant habitat available for migratory fish. A dam removal on the lower Neversink River in 2004 opened up the entire historic habitat available for American shad, while also improving access for American eel and sea lamprey. In the case of a river like the main-stem Schuylkill River, fish passage structures allow fish like shad to access upstream portions of the river; although our analysis does not recognize this degree of connectivity due to difficulties in fairly assessing where fishways effectively mitigate barriers that dams pose to most fish.

Despite the fact that the main-stem and connected portions of its many tributaries together provide over 500 miles (805 km) of unblocked aquatic habitat, the Delaware River's tributaries have suffered significant fragmentation from the construction of over 1,400 dams in the 1800s and 1900s. Notwithstanding the fact that they lack a direct connection to the main-stem or bay, some tributary stream networks in the Basin still offer significant mileage of connected habitat for resident fish. Some of the largest connected stream networks include the headwaters of the West Branch, the East Branch, the Lehigh River, and the Schuylkill River; a significant section of the middle Schuylkill also lacks tracked dams (Fig 5.3.6). The ability to move locally within stream systems like these is important to many species. In particular, potadromous species, such as the white sucker, make instream migrations to complete their life cycles.

It is important to note that while some of the shorter stream systems (e.g, small coastal streams) may not have especially high values in terms of total connected stream length, these streams, which are often highly productive, are 100% connected from their headwaters to the Bay, allowing fish access to their full historic range of stream habitats (e.g., Red Lion Creek or Augustine Creek in Delaware or Oranoaken Creek or Bidwell Creek in New Jersey).

5.3.3.4 Past Trends

In 1985, the Delaware River Basin Fish and Wildlife Management Cooperative identified three priority rivers for fish passage efforts: the Brandywine, Schuylkill, and Lehigh Rivers. How far upstream fish can swim in each of these rivers has changed over time in two of these three rivers as fish passage efforts like dam removal and fishway installation have been implemented (Fig 5.3.7).

On the main-stem Brandywine, fish ladders were installed during the mid-1970' on three of the first four dams, all located within the first four miles of the river. However, after several years of monitoring, the fish ladders were found to be ineffective and were removed. The Brandywine Conservancy has published feasibility studies for addressing fish passage for American Shad in the Delaware (2005) and Pennsylvania (2009) portions of the watershed. The studies included the 11 main-stem Brandywine dams in Delaware (~14 miles/23km of mainstem habitat) and 10 of the 28 current dams in Pennsylvania.

On the main-stem Schuylkill, three fish ladders and four dam removals since 2006 have increased access from river mile 15 up to river mile 100, a dramatic improvement. The effectiveness of the three fish ladders is still largely unknown, with only the Fairmount Dam fish ladder having associated long-term monitoring results published. In addition to the main-stem projects, between 2003 and 2007, five dams have been removed on the Perkiomen Creek main-stem, three on the Wyomissing Creek, and one each on the Tulpehocken and Pickering Creeks.

On the main-stem Lehigh, the first two dams had fish ladders (Easton & Chain) installed in 1994 and later retrofitted in 2000. The third dam, Hamilton St., had a fish ladder installed in 1984. A main-stem dam farther upstream, Palmerton Dam, was removed in 2006. After years of monitoring at both Easton and Chain dams, these fish ladders have been determined to be ineffective in passing their target species, American Shad. As a consequence, the Wildlands Conservancy and the PA Fish & Boat Commission recently requested proposals to evaluate the removal of Easton and Chain dams (July 2011) in the hopes of improving fish passage at these locations. Northampton Dam, the last of the lower four dams, is expected to have a fish passage feasibility study initiated in early 2012. In addition to these mainstem Lehigh projects, between 2000 and 2010, a total of 5 dams have been removed on Saucon Creek, East Branch Saucon Creek, Jordan Creek, Little Lehigh Creek, and Mahoning Creek. In addition to these three tributary watersheds, there are active fish passage efforts underway in smaller tributaries such as Ridley Creek (DE/PA), Pennypack Creek (PA), Bushkill Creek (PA), Lopatcong Creek (NJ) and the Musconetcong River (NJ).

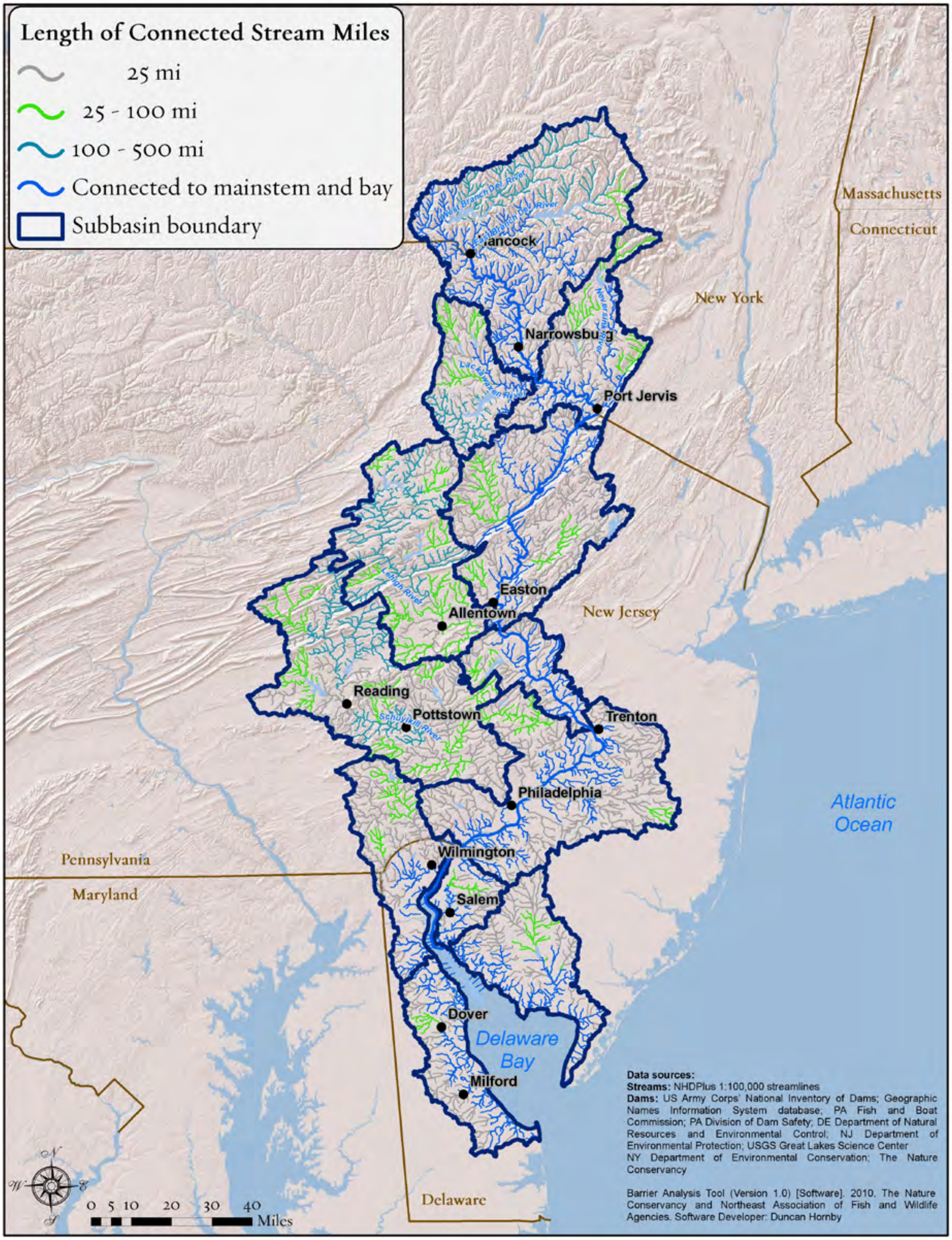

Figure 5.3.6 Connected stream networks in the Delaware River sub-basins.

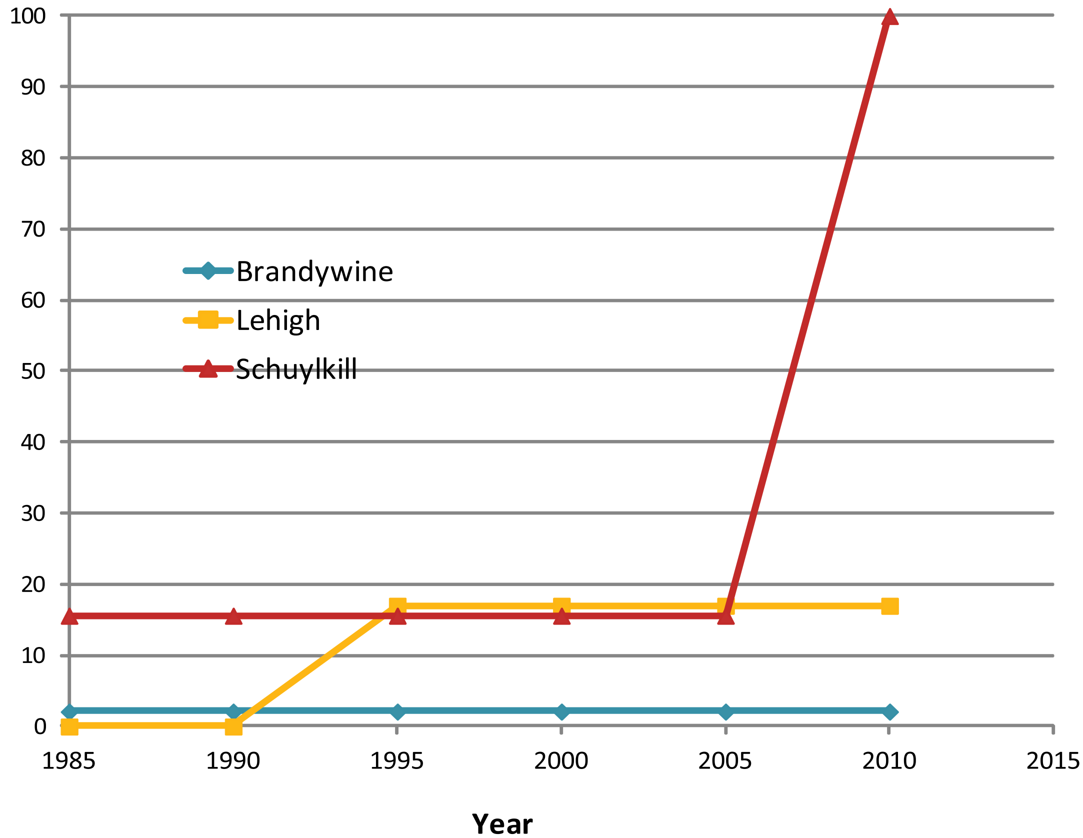

Figure 5.3.7 Number of connected stream miles accessible from the main stem Delaware River or Bay between 1985 and 2010 for each of the three priority fish passage rivers.

5.3.3.5 Future Predictions

The importance of river connectivity and associated fish passage is being recognized by many water resource agencies and the public and is evident in the recent number of dam removal projects and feasibility studies recently completed or currently underway. In addition to the direct impact on fish habitat, the relationship between keystone species such as freshwater mussels and their dependence on certain fish species for reproduction and colonization should only add momentum to addressing fish passage. Unless Basin prioritization is revisited, fish passage projects will likely continue to be haphazardly located throughout the Basin with more action occurring in tributaries with active watershed based organizations and cooperative dam owners rather than in strategic locations.

5.3.3.6 Actions and Needs

Financial resources for addressing fish passage within the Basin are limited, and there is a need for an updated comprehensive evaluation of where best to prioritize fish passage. The prioritization needs to consider the best ecological return for each location addressed as well as the suitability of potential new habitat. An ongoing effort since 2008 by the Northeast Association of Fish and Wildlife Agencies and The Nature Conservancy (TNC), called the Northeast Aquatic Connectivity (NAC) Project, has developed tools and an initial assessment of opportunities for restoration of stream system connectivity across the Northeastern U.S. With input from the NAC workgroup, TNC calculated 72 ecologically relevant metrics for almost 14,000 dams across the region and developed tools to allow for tailored assessment of ecological returns of reconnection projects. Tools and final products include two assessment scenarios that rank dams for benefits for anadromous fish and for benefits for resident fish, produced using a subset of metrics weighted by the workgroup. While these products and tools will help inform prioritization efforts, site-specific factors still need to be considered in project selection. In addition to the forthcoming Northeast Aquatic Connectivity Project, Senator Tom Carper (Delaware) recently introduced the Delaware River Basin Conservation Act of 2011, which would establish a federal program at the U.S. Fish and Wildlife Service (USFWS) to coordinate voluntary restoration efforts throughout the Basin and oversee up to $5 million per year of grant funding. It is envisioned that a basin-wide fish passage prioritization project would be an ideal project worthy of funding through the Act and would help guide future distribution of grant monies. The fish ladders installed in the Lehigh River have also demonstrated that not all fish passage "remedies" are equal, with some being more successful than others. In cases where a dam no longer serves a critical use such as for public water supply, the first remedial option should be removal. In addition, where regulatory opportunities exist with dam owners during permitting actions, regulatory agencies need to adopt and implement a consistent approach as to when and why fish passage needs to be addressed. Many dam owners have argued that if anadromous fish are not present downstream of their dam, then there is no need to address fish passage. For dam locations that do not have anadromous fish downstream, addressing fish passage is still important for resident species. From the perspective of both anadromous and resident fish, assessing the degree to which road/stream crossing structures also are creating barriers to fish passage will be important, as well. While we currently lack good data, pilot field surveys conducted by The Nature Conservancy and others will provide some insight on the prevalence of problematic culverts within select tributary watersheds in the Basin. Following ecological standards for culvert design and replacement could be helpful to restore connectivity currently hindered by these small structures.

5.3.3.7 Summary

The Basin has experienced a large number of fish passage projects, primarily targeting American Shad, during the past 10 years. Most of the fish passage projects are occurring in Pennsylvania, with both financial and technical support from state resource agencies. Although three large tributaries were targeted in 1985 for priority consideration, it appears that the only tributary with significant progress may be the Schuylkill River. Recent fish passage efforts do not appear to be a component of a larger restoration plan. A new basin-wide reassessment of fish passage priorities is needed to ensure that limited resources are being targeted in an efficient and effective manner.

5.3.4 Hydrological Impairment

5.3.4.1 Introduction

Natural variations in hydrologic regime—the magnitude, timing, frequency, duration, and rate of change of stream flow—are critical for sustaining healthy river systems (Poff et al. 1997, Richter et al. 1997). Healthy floodplains also are dependent upon natural flows, as they require interaction with rivers whose flow regimes have sufficient variability to encompass the flow levels and events that support important floodplain processes (Opperman et al. 2010). Alterations to the natural flow regime of a river result from a variety of sources, such as flood control, water supply and hydropower dams, as well as water withdrawals and development in the watershed. Paved and other hard surfaces, collectively referred to as impervious cover, often increase the volume of and rate at which precipitation runs off into the stream channel and can increase the flashiness of streams (Leopold 1968). Impairment of a river's natural hydrologic regime can cause various negative impacts throughout a watershed. Dams that store large amounts of water can significantly change amounts of streamflow downstream of the dam, as well as change seasonal patterns of high and low flows on which many aquatic organisms depend (Poff et al. 1997). In addition, large dams change sedimentation patterns, potentially depriving the river downstream of the dam and causing significant changes in the stream channel and bed. Other impacts include changes in water temperature and nutrient transport, which in turn affect both aquatic and riparian species (Poff and Hart 2002).

5.3.4.2 Description of Indicator

All dams do not have the same effects on downstream rivers, and consequently, using one indicator to predict potential hydrological alteration is difficult across the entire Basin. However, one important indicator of potential alteration to the natural hydrologic regime is the ratio of upstream dam storage to mean annual flow downstream (Graf 1999). This ratio is calculated by expressing the cumulative volume of water stored by upstream dams as a percent of the mean annual flow of each downstream river segment. As this proportion increases, so does the likely alteration to natural stream flow. Ratios indicative of a high risk of hydrologic alteration have been demonstrated to be > 50% (Zimmerman and Lester 2006). Using storage values available in state and Army Corps of Engineers (National Inventory of Dams) databases and mean annual flow values associated with NHD+ streamlines, we applied the Barrier Analysis Tool (BAT, v.1) to calculate the percent of mean annual flow that is stored in upstream dams in the Delaware River Basin.

This indicator does not take into account day to day reservoir operations or specific dam configuration, which can influence the degree of hydrologic alteration in either a positive or negative way. Furthermore, this indicator also does not reflect the effects of other water diversions or withdrawals in the Basin, so it is limited to potential impairments to hydrologic regime caused only by dam storage. However, the basin-wide assessment of the risk of hydrologic impairment due to high dam storage is still a useful indicator; across large and small rivers, it can help identify which stream and river reaches may be suffering the hydrologic (and associated ecologic and biologic) impacts of upstream dams and which dams may warrant further investigation to address potential streamflow alteration.

In order to identify places most likely to be suffering hydrologic impairment due to land use change, examining the percent cover of impervious surface within a watershed can provide a useful complement to the measure of upstream dam storage. The high amounts of impervious cover associated with many highly developed areas are likely to cause hydrologic alteration downstream unless there are adequate stormwater management systems in place. The higher the percent cover of impervious surface across a small watershed, the more likely its streams are to be suffering hydrologic impairment. Because this metric cannot take into account effective stormwater management, it also should be used as a first-cut indicator to identify places that likely would benefit from stormwater management systems if they are not already in place.

5.3.4.3 Present Status

As many dams in the Basin are run-of-river dams and have relatively little effect on hydrologic regime, the vast majority of stream miles within the Basin are at low risk of hydrologic alteration, as indicated by their ratio of dam storage to mean annual flow value (Fig 5.3.8). However, over 300 stream and river miles (483 km) within the Basin could be considered at high risk as indicated by ratio values of >50%. Of these 300 miles, over 130 miles (209 km) of high-risk streams and rivers are those which drain less than 38 square miles (9842 ha). High ratios might be expected in these headwater areas where dams occur in small streams that have relatively low mean annual flow values. High risk on larger rivers may be caused by the cumulative storage of many dams upstream or by a major reservoir with significant storage capacity (or a combination of the two). Despite the limitations of the Basin-wide analysis of the risk of hydrologic impairment due to high dam storage, this ratio is still a useful indicator of locations where impaired hydrology may be occurring and affecting the health of our streams and rivers. While some significant impacts are occurring in the Delaware River Basin, most streams and rivers are at low risk of impairment from dam storage.

Similarly, the vast majority of watersheds within the Basin have relatively low (< 10 %) impervious cover (Fig 5.3.9). However, streams in or downstream of urbanized areas, particularly those with outdated or insufficient stormwater management in place, are likely to be suffering negative impacts of altered hydrology as well. Most at-risk watersheds are concentrated around the cities of Wilmington, DE, Philadelphia, PA, and Camden, NJ, though watersheds along the Lehigh, Schuylkill, and Maurice Rivers also may be experiencing substantial hydrologic impairment due to land use change. Localized land change certainly may also affect hydrology within a watershed, but this basin-wide analysis helps to identify where the greatest impairment is likely to be occurring.

5.3.4.4 Past Trends

Most of the Basin's large reservoirs were completed between 1960-1980 and were not specifically designed to operate with the longitudinal (high and low) and/or the temporal (seasonal) conservation flows that may be needed to maintain native aquatic communities. Recent advances in ecological flow science have resulted in many water resource agencies beginning to factor ecological flow needs into the way that large reservoirs are managed. Some smaller Basin reservoirs currently do not have any conservation release requirements, while most of the larger reservoirs have release requirements based on assimilative capacity needs ("Q7-10" - the consecutive 7-day flow with a 10-year recurrence interval) as opposed to one based on aquatic resource needs. Recent changes adopted by the Decree Parties for the three New York City Basin reservoirs have started to incorporate aquatic resource needs into their reservoir operation plans.

Most of the Basin's existing impervious cover was created prior to modern stormwater management (pre 2000). If any stormwater management did occur prior to 2000, it tended to focus on large storm events (>10 year storm). Modern stormwater management requirements have tended to focus on a broader range of rain events (0-100 year storm events), along with minimum infiltration requirements. The modern stormwater management requirements have largely centered on trying to maintain the existing hydrology of a project site from pre to postdevelopment conditions.

5.3.4.5 Future Predictions

As ecological flow science progresses and native aquatic communities' needs are further identified, water resource agencies can start to factor those data into the management of Basin reservoirs. New reservoirs will almost certainly be designed and permitted to consider ecological flow needs, while existing reservoirs operations are reviewed during the permit renewal process, which provides opportunities for operational revisions based on the latest science.

Stormwater management will need to focus in two areas – new development and retrofitting existing impervious cover. Almost all new development in the Basin is subject to modern stormwater management requirements. It is anticipated that the level of hydrological impairment due to "new development" will be minimal compared to the existing hydrological impairment caused by existing impervious cover.

5.3.4.6 Actions and Needs

A study of ecological flow needs to protect species and key ecological communities for the range of habitats in the Delaware River Basin is necessary in order to provide the scientific basis for any future modifications to reservoir operation plans.

Developing a strategy to deal with existing hydrological impairments due to existing impervious cover is necessary. Options range from mandatory stormwater management retrofits during the redevelopment of a site to voluntary retrofits incentivized by the implementation of stormwater runoff fees.

5.3.4.7 Summary

While most Basin streams are at low risk of hydrological impairment due to dam storage, some significant impacts are occurring in localized areas. The incorporation of ecological flow needs into reservoir management will likely increase in the future as those needs are further identified, which should result in a gradual minimization of impacts in those localized streams.

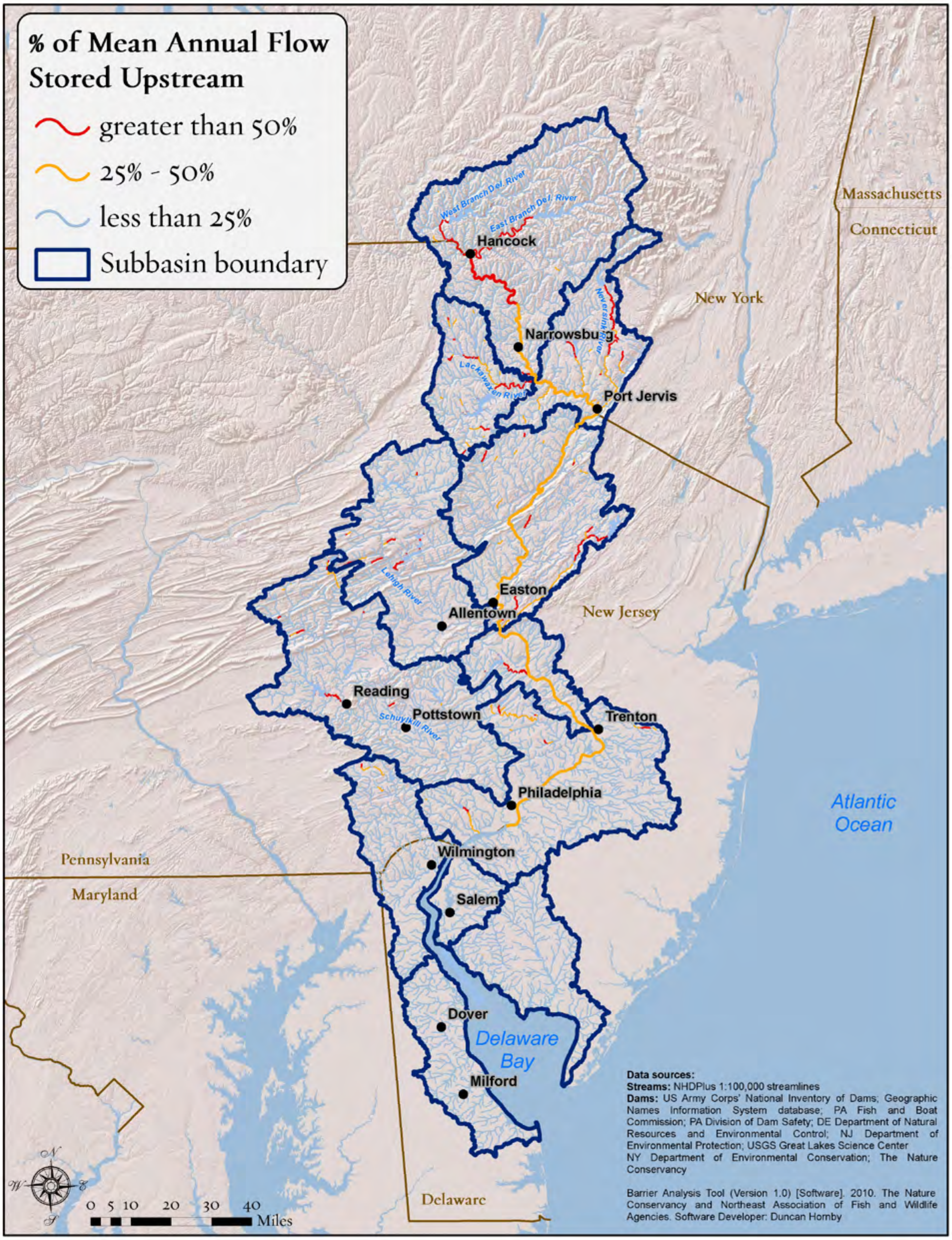

Figure 5.3.8 Ratio of upstream dam storage to mean annual flow for river reaches within Delaware River sub-basins.

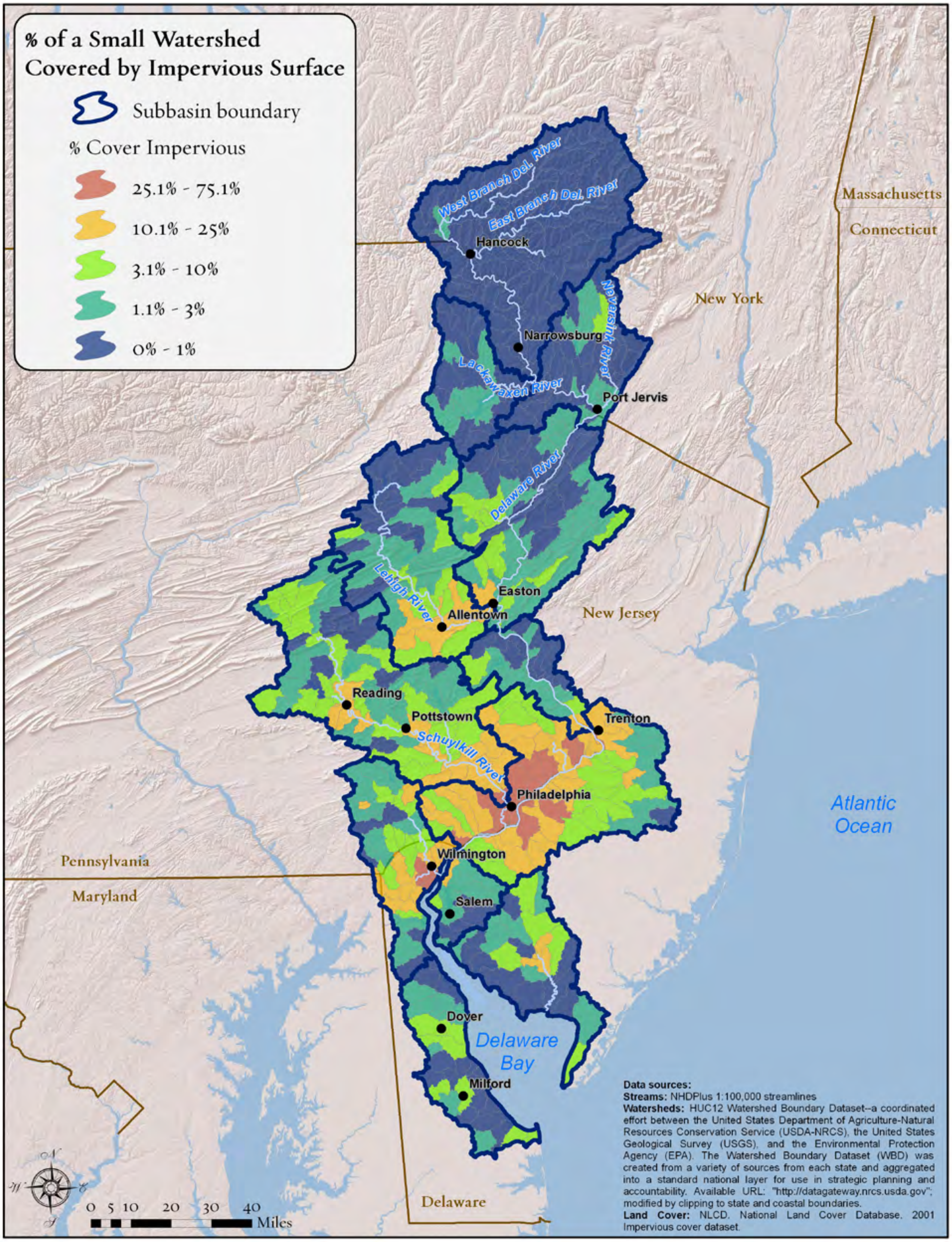

Figure 5.3.9 Percent cover by impervious surface across small watersheds in the Delaware River Basin.

5.3.4.11 Example Effects of Dam Storage and Operations on Hydrologic Impairment: Neversink River

Robert Tudor[1] • Ellen Creveling[2] • Michele M. DePhilip[3] • Chad Pindar[1]

1. Delaware River Basin Commission; 2. The Nature Conservancy, New Jersey; 3. The Nature Conservancy, Pennsylvania

The basin-wide indicator of dam storage ratios does not take into account actual dam operations. For example, this analysis indicates a high level of alteration downstream of the Neversink Reservoir. Indeed, the biologic effects of hydrologic alteration have been documented in the Neversink River, where macroinvertebrate surveys indicated that species composition in the river downstream of the reservoir showed signs of degradation similar to stretches impaired by acidity in other parts of the watershed (Ernst et al. 2008).

Altered temperatures and low flow in river stretches immediately downstream of the reservoir appeared to favor Chironomidae taxa over Ephemeroptera, Plecoptera, and Trichoptera taxa, similar to how pH and aluminum in the East Branch of the Neversink River appeared to influence macroinvertebrate composition there. This change in the biotic community of the river downstream of the reservoir likely was caused by adverse effects from dam storage (Ernst et al. 2008). However, more recently, a detailed study of the effects of changes in the management of the Neversink Reservoir just within the past few years illustrates that recent management changes have improved the degree of alteration to the Neversink River's natural hydrologic regime (Moberg et al. 2010).

Figure 5.3.4.11.1 below shows how the natural range of variability in flow on the Neversink has changed with the implementation of the Flexible Flow Management Plan (FFMP). Whether the biotic communities of the Neversink River downstream of the reservoir have shown any positive response to the return of a more natural hydrologic regime has not yet been studied.

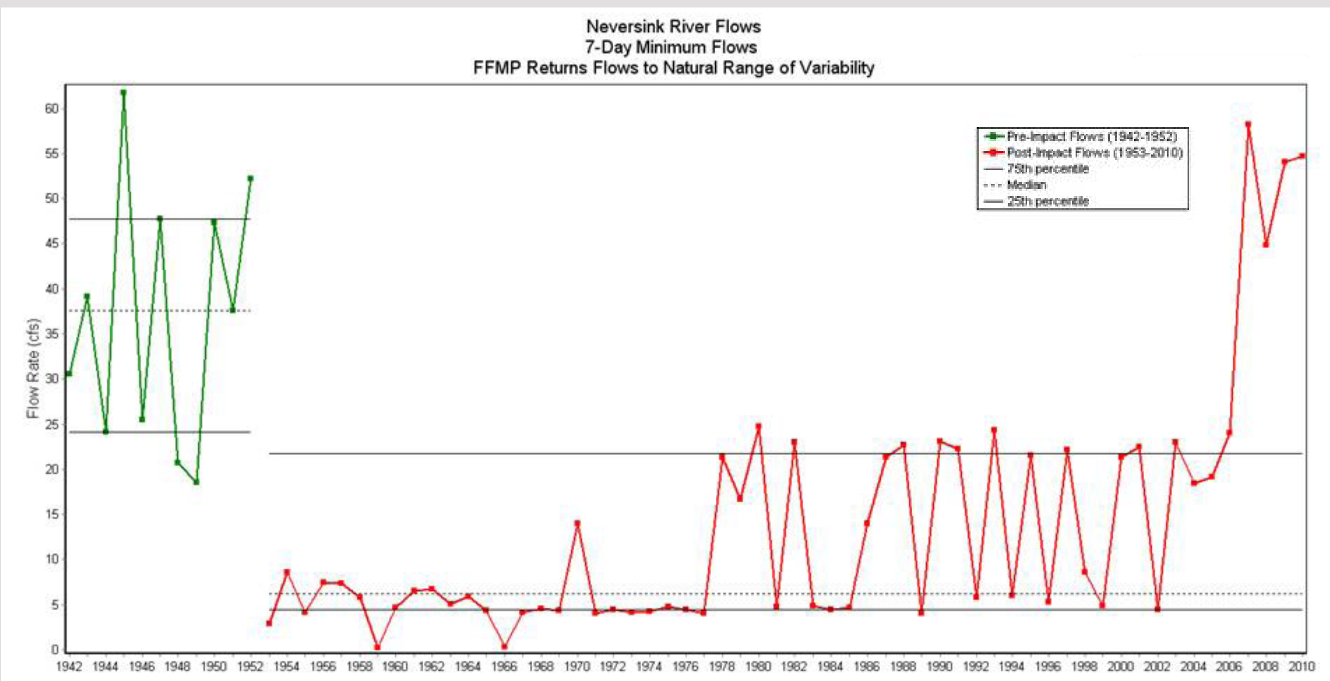

Figure 5.3.4.11.1 Neversink River 7-day minimum flows from 1942-1952 (green) and 1953-2010 (red).

While most Basin streams are at low risk of hydrological impairment due to existing impervious cover, there are significant impacts in the older urban/suburban areas of the Basin. Implementing stormwater management on existing impervious cover is expensive and may take several decades to address.

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Suggested Citation for this Chapter

Tudor, R., E. Creveling, M. M. DePhilip, C. Pindar. 2012. “Chapter 5.3 - Nontidal Habitats” in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 196-212.

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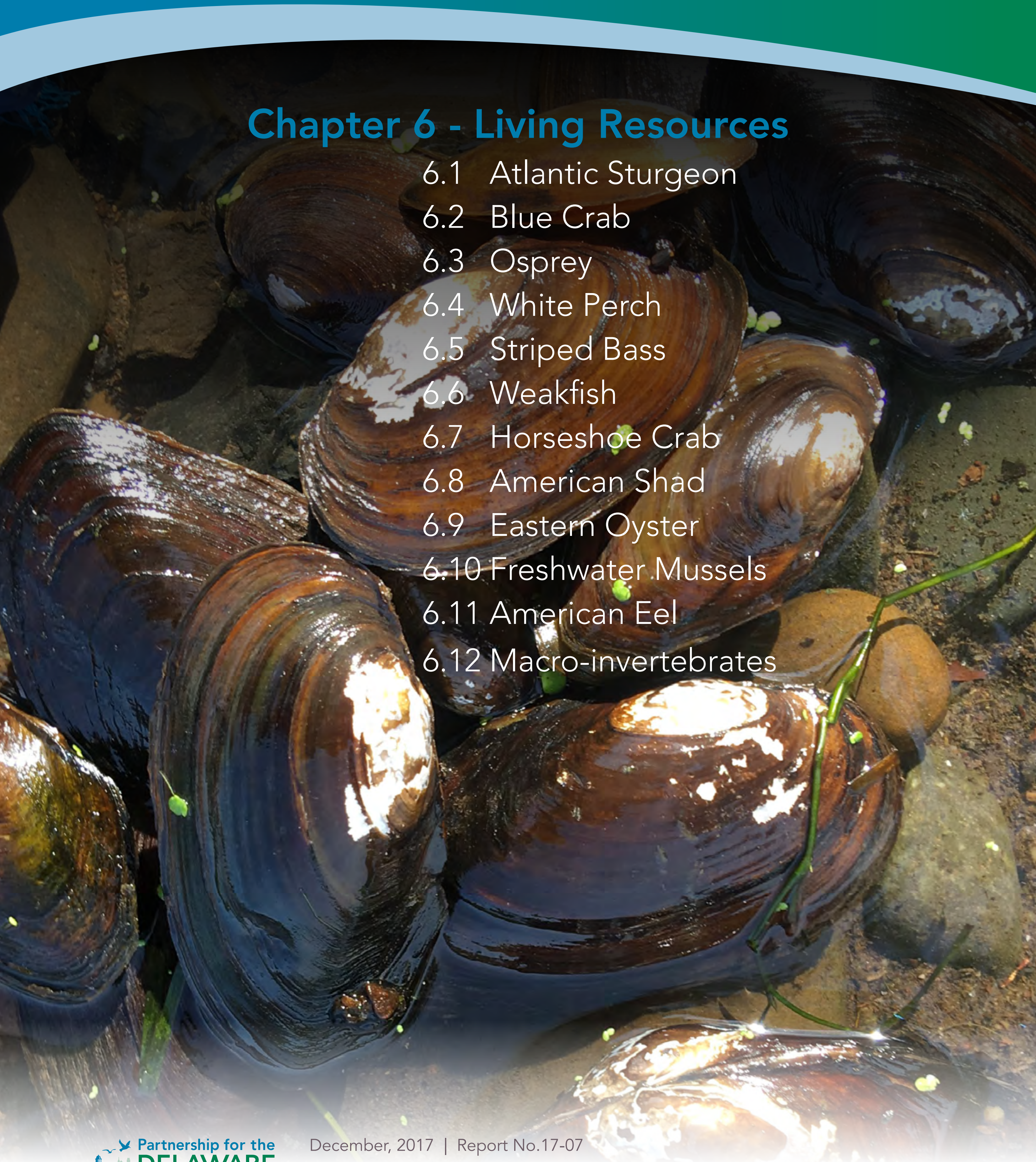

Chapter 6 - Living Resources

Partnership for the DELAWARE ESTUARY

December, 2017 | Report No.17-07

A publication of the Partnership for the Delaware Estuary—A National Estuary Program

6. Living Resources

6.1 Atlantic Sturgeon

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6.1.1 Introduction

Historically, Atlantic Sturgeon, *Acipenser oxyrinchus oxyrinchus*, were reported in the Delaware River as well as most major rivers on the eastern seaboard of North America ranging from the Hamilton Inlet on the Atlantic coast of Labrador to the St. Johns River in Florida. The species is in the family Acipenseridae, a category of ancient bony fishes that have been able to survive as a group in contemporary environmental conditions (Detlaff et al. 1993). Atlantic sturgeon are late-maturing anadromous fish that may live up to 50 years, reach lengths up to 14 feet (4.3 m), and weigh over 800 pounds (364 kg). They are distinguished by armor-like plates called "scutes" and a long snout. They are opportunistic benthic feeders filtering quantities of mud along with their food, which consists of aquatic invertebrates (Vladykov and Greely 1963).

Mature Atlantic sturgeon (Fig 6.1.1) migrate from the sea to fresh water in advance of spawning. Females first mature at ages ranging from 7-19 years old in South Carolina to 27-28 years old in the St. Lawrence River. Males can be somewhat younger at first spawning. The Delaware River population of Atlantic sturgeon has been determined to be genetically similar to those of the Hudson River, but through range-wide genetic analysis of nuclear DNA at least 6 sub-populations were suggested including one for the Delaware River distinguishable from the Hudson River stock (King et al. 2001).

In the Delaware River, first-maturing females are likely to be at least 15 years old. Spawning occurs in flowing fresh waters with a hard bottom. Shed eggs are 2-3 mm in diameter and become sticky when fertilized frequently becoming attached to hard substrates or submerged detritus until hatching in several days. After hatching occurs, juveniles remain in fresh water for several years but have been documented to out-migrate to coastal areas in their 3rd year (Sweka et al. 2006). Once juveniles out-migrate from their natal river they are known to frequent distant estuary systems (Secor et al. 2000); tagged age-0 juvenile fish stocked in the Hudson River in 1994 were found in the Chesapeake and Delaware Bays in 1997 (Bain 1998).

Mature individuals also frequent estuaries distant from their natal river. Studies performed in the Hudson River using pop-up satellite archival tags showed that the majority of adult Atlantic sturgeon captured and tagged in the Hudson during spawning season eventually out-migrated to the mid-Atlantic Bight, but one individual traveled north to the Bay of Fundy and another went south to coastal Georgia (Erickson et al. 2011). Mature Atlantic sturgeon are of great potential commercial value for both flesh and roe, the latter being known as caviar. Although there is an occasional report of Atlantic sturgeons being caught with rod and reel, the species is not known for recreational fishing importance.

The portion of the Delaware River Basin available as habitat extends from the Delaware Bay to the fall line at Trenton, NJ, a distance of 140 river kilometers (rkm). Within this reach, habitat suitability is unknown due to anthropogenic effects on the historic habitat as a result of industrial development, dredging, and water quality issues. The exact spawning locations of Atlantic sturgeon in the Delaware River are unknown; based on reported catches in gill nets and by harpoons during the 1830s, they may have spawned as far north as Bordentown, south of Trenton, NJ (Atlantic Sturgeon Status Review Team 2007).

Figure 6.1.1 A) Young-of-year Atlantic sturgeon captured in the Delaware River in 2009. Photo courtesy of Delaware Department of Fish & Game; B) Mature Female Atlantic sturgeon. Photo credit: U.S. Fish & Wildlife Service.

6.1.2 Description of Indicator

The primary indicator is the catch per unit effort (CPUE) from the Delaware Division of Fish and Wildlife (DE DFW) (Park 2016), which has conducted targeted Atlantic sturgeon gill net surveys using variable mesh research gill nets in most years since 1991 with the exception of 1999-2000, 2002, 2005-2006, and 2013. The survey has changed both sampling sites and gear over time. Surveys prior to 2009 employed nets with multiple mesh sizes in each net, including both larger mesh sizes which target larger juveniles and adults, and smaller mesh sizes, which target young sturgeon from 0 to 3 years of age. From 1991-1996, the surveys focused on the location around Artificial Island, well below the mouth of the Chesapeake & Delaware Canal. Surveys from 1997 to 2008 included sampling at sites further upriver, including sites where young-of-the-year were later caught in 2009; no captures of young-of-year sturgeon occurred in these earlier years, however. Beginning in 2009, only smaller mesh nets (51 and 75 mm) were employed, targeting 0 to 3 year old sturgeon. All sample sites were moved far upriver from the Artificial Island area, including sites that had also been sampled from 1997 through 2008: Fort Mifflin (rkm 148), Tinicum Island (rkm 142), Marcus Hook anchorage (rkm 127), Marcus Hook bar (rkm 122) and Cherry Island Flats (rkm 119) (Fig 6.1.2). These were preferred areas as they were flat bottom sites free of snags, away from heavy ship traffic, near the freshwater-brackish water interface and out of the main channel in 3-8 m of depth.

A secondary indicator is the catch of juvenile sturgeon in the DE DFW research trawl survey program, consisting of the Adult Fish and the Juvenile Fish Surveys. The former employs an otter trawl net with a thirty-foot headrope, while the latter employs a sixteen-foot shrimp try net. These two surveys sample a fixed station design. The Juvenile Trawl samples sites in the lower River through the lower Bay from April through October mainly in near-shore areas, while the Adult Trawl samples only sites in deeper waters in Delaware Bay from March through December.

6.1.3 Present Status

In 2012, the National Marine Fisheries Service, under the authority of the Endangered Species Act, declared the New York Bight Distinct Population Segment of Atlantic Sturgeon to be endangered. The Delaware River spawning stock is included in this segment, along with the Hudson River stock. This declaration was controversial. The Endangered Species Act does not set a firm criterion for a finding that a species is endangered, leaving the decision to be possibly affected by subjectivity. Previously, due to low range-wide population levels, in 1998 a moratorium on all Atlantic sturgeon harvest in U.S. waters was adopted by the Atlantic States Marine Fisheries Commission, enforceable under the provisions of the 1993 amendments to the Atlantic Coastal Fisheries Cooperative Management Act (P.L. 82-721). The moratorium remains in effect to date with no permitted recreational or commercial harvest.

Hale et al. (2016) produced an estimate of the absolute abundance of juvenile Atlantic sturgeon in the Delaware River in 2014 based on tag-recapture data. The estimated abundance is 3,656 fish; as is common with tag-recapture-based estimates of absolute abundance, the confidence intervals are relatively wide, between 2,000 to 33,000 thousand fish (Hale et al. 2016), meaning that the abundance of juvenile sturgeon in the River ranges between several thousand to several tens of thousands.

While the results of Hale et al. (2016) are good news on the success of spawning in 2014, sampling efforts from 2009 through 2012 had sporadic results, suggesting that successful spawning did not occur in every year; specifically, no young-of-year fish were collected in 2010 and only one was collected in 2012. In several years during this period, dissolved oxygen levels were recorded at, below or near the criterion of 3.5 mg/l. At the median summer temperature of 27°C, 3.5 mg/l is only 44% of oxygen saturation. Inspection of the occurrence of low levels of dissolved oxygen and high temperatures in these four years suggested the possibility that few to no larvae may survive in the years with the lowest levels of dissolved oxygen, which may also be the years with the highest peak temperatures (Kahn and Fisher 2012). The youngest larvae

Figure 6.1.2 2009 sampling sites (yellow call out boxes) used as part of an early juvenile Atlantic sturgeon telemetry study by Delaware Department of Fish and Wildlife (DE DFW). Red dots are acoustic receivers. Map courtesy of DE DFW.

appear to be the most vulnerable to low oxygen levels, based on research on shortnose sturgeon, and the lowest oxygen levels usually occur in July, when larvae are only weeks old.

Results of the DE DFW gill net sturgeon surveys, employing a research net with a mix of different mesh sizes, show a steep decline in catch-per-unit of effort of larger juveniles (> 600 mm) from 1991 to the mid-1990s, with low levels continuing through to 2008, the last year in which the survey included the larger mesh sizes (Fig 6.1.3), indicating that relative abundance of these older juveniles declined during the 1990s, but the decline may not have been caused by a decline in the Delaware River spawning stock itself. Sub-adults of this size class seasonally wander to non-natal estuaries, so the decline may reflect declines in stocks from other rivers.

Beginning in 2009, the survey targeted smaller sturgeon (ages 0-3) exclusively, by employing only nets with small mesh. Catches of early stage juveniles (<600 mm total length) increased dramatically in 2009 including the capture of 34 young-of-year fish ranging in size from 178 to 349 mm total length (Fisher 2009) (Fig 6.1.3). Few, if any, young-of-year Atlantic sturgeon had been collected in decades prior to 2009. The DE DFW Juvenile Fish research trawl survey had previously captured three young-of-the-year sturgeon (1989, 1990, 1993) in locations upriver of Artificial Island (Cherry Island Flats and the western side of Pea Patch Island), but was not able to determine if these fish were Atlantic or shortnose sturgeon. The collection of over a score of young-of-year fish in 2009 and 2011 showed that successful spawning took place in the Delaware in those years and that there is some suitable spawning habitat available. Above average rainfall during the sampling period and targeted sampling, focused exclusively on early stage juvenile habitat with small mesh nets, could have contributed to the relatively large catch of early stage juveniles.

Recently, the sturgeon catches in the secondary indicator, the Adult Finfish and the Juvenile Finfish Research Trawl Surveys have increased in consistency, with the catch in 2011 showing the highest catch on record (Fig 6.1.4). The fact that both surveys have seen more consistent catches indicates that spawning success in the River may have become more consistent and of greater magnitude over the last decade.

The use of acoustic tagging methods have produced a large increase in our understanding of habitat used by this species. Scores of sturgeon captured in the Estuary have been tagged with acoustic tags, which transmit to receivers along the Estuary and into the Atlantic. Hundreds have been tagged with passive integrated transponders. Results from tracking acoustically tagged sturgeon (Simpson and Fox 2006) indicated that the present day lower limit of Atlantic sturgeon spawning is likely the upper limit of salt water intrusion near Tinicum Island (rkm 136) while the upper limit is likely at the fall line near Trenton, NJ (rkm 211).

In the late fall of 2009, 25 young-of-year sturgeon (262-349 mm total length) were tagged with acoustic transmitters made by VEMCO. All fish were released at the Marcus Hook anchorage (expanded map section) from September 24th to November 9th, 2009 with the majority of fish being released on October 27th. Manual tracking locations were used to determine fine scale habitat. In this monitoring approach, biologists used hand-held acoustic monitors to locate tagged fish. Weekly tracking ranged from the Delaware Memorial Bridge to the mouth of the Schuylkill River. During the tracking period several individuals moved upriver out of tracking range. Preliminary results indicate tagged early-stage juveniles are ranging from New Castle flats, DE to Roebling, NJ with the highest concentration located in the Marcus Hook anchorage (M. Fisher, formerly DE DFW, personal communication).

The passive receiver array system maintained by the DE DFW, Delaware State University and Environmental Research Consultants, Inc (ERC), comprises over 70 receivers in various locations throughout the Delaware Bay and River, the Chesapeake and Delaware Canal, and the coast of Delaware and New Jersey. The array collected over 40,000 detections from the 25 early stage juvenile sturgeon that were implanted with transmitters, including information on seasonal individual movement and behavior patterns of this 2009 year class of Atlantic sturgeon. Four individuals migrated upriver at different times over the winter months while

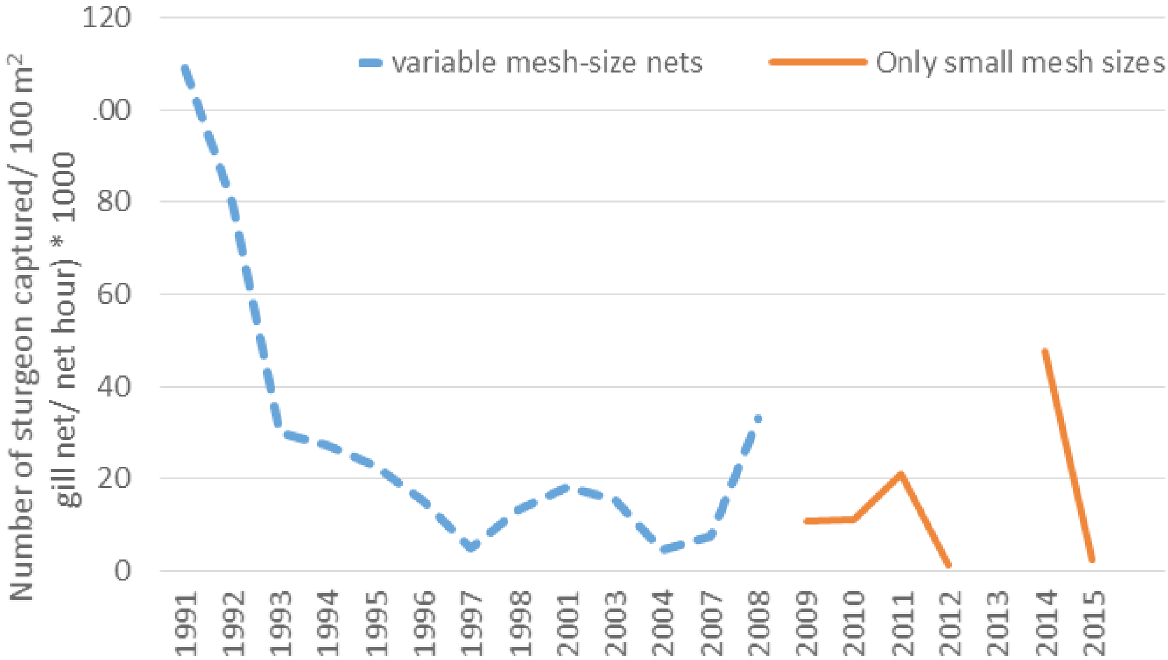

Figure 6.1.3 Primary indicator of sturgeon trend in abundance by age category in the tidal Delaware River and Bay, 1991 – 2015. Data from Park (2016). Number caught in 2008 was elevated due to use of telemetry to locate sampling sites. No sampling was conducted in 2013 due to the announcement of Endangered status in 2012.

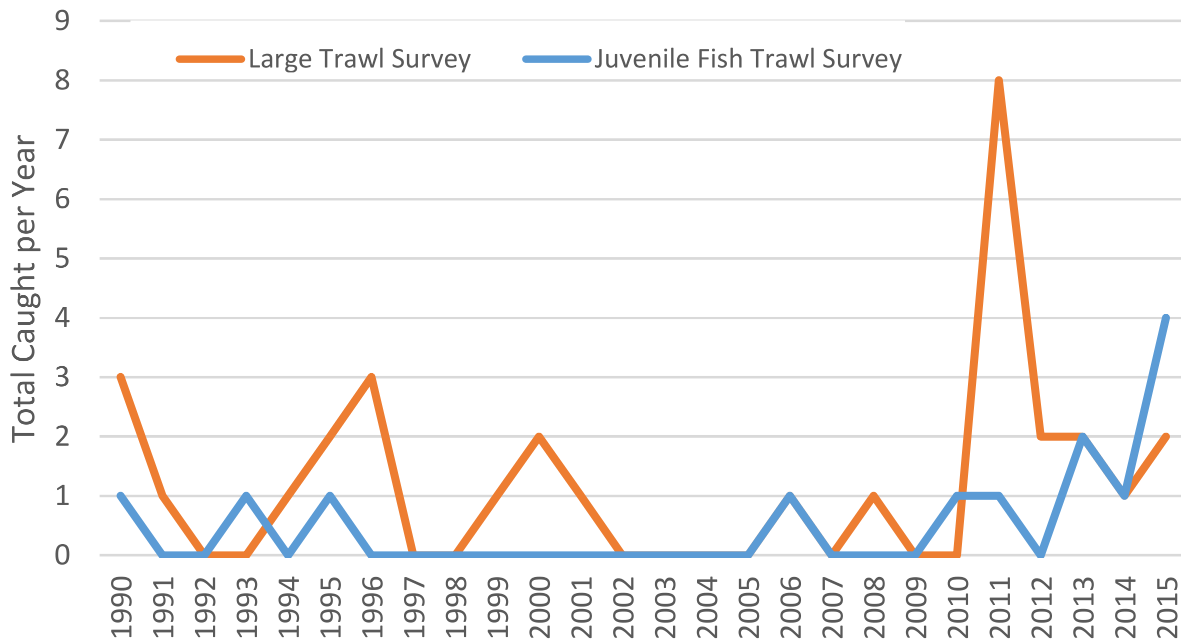

Figure 6.1.4 Secondary indicator of trends in abundance of Atlantic sturgeon in the Delaware Bay and River. Total number caught per year by the Delaware Division of Fish and Wildlife's Adult Fish Trawl Survey in Delaware Bay and the Juvenile Fish Trawl Survey in the Bay and River. Note that none of the sturgeon caught in the surveys were adults. Sampling design and total number of tows are basically identical each year.

others remained in a confined home range in between receivers. Detections ranged from New Castle, DE (rkm 105) to Roebling, NJ (rkm 199), well upstream of the head of tide, with individual movements of over 20 rkm per day. The highest concentration of these young-of-year fish occurred at the Marcus Hook anchorage. This location, just upriver from the Delaware-Pennsylvania border, is usually visually prominent due to one or more tankers riding at anchor. It should be noted that cooperation between researchers and compatibility of technology made these study results possible and is essential for understanding the movements of this species.

The presence of early-stage juveniles in the Marcus Hook anchorage is consistent with findings of Sommerfield and Madsen (2003), that the substrate composition between Marcus Hook and Tinicum Island (Fig 6.1.2) may represent suitable spawning habitat for Atlantic sturgeon. The majority of the hard-bottom substrate zones, particularly the coarse-grained bedload areas, either neighbor or are within the shipping channel. However, the presence of hard-bottom substrate within the shipping channel may also be a limiting factor in terms of spawning success, potentially exposing adult Atlantic sturgeon to mortality due to ship strikes (Brown and Murphy 2010).

The DE DFW and Delaware State University researchers record reports of sturgeon carcasses (Fig 6.1.5), which are attributed to strikes from tugs, tankers, and freighters. The DE DFW has placed a notice with a call-in phone number in the annual fishing guide. The guide is distributed to roughly 125,000 anglers annually. Social media is also employed as outreach to increase reports of sturgeon carcasses. An increase in observed reports occurred between 2010 and 2015 (mean annual reported was 19.6) compared to the period from 2005-2009 (mean annual reported was 8.2). The increase could be due to higher reporting rates from social media publicity efforts. However, it could also be due to increased sturgeon abundance or to a higher kill rate. The large majority of carcasses exceeded 1,500 mm, meaning they are of adult size. Delaware State University researchers will conduct a study of the rate that carcasses are reported in 2017. If the reporting rate can be estimated, then the magnitude of ship strike mortality can be estimated.

The Cooperative Endangered Species Conservation Fund provides grants to states and territories to participate in a wide array of voluntary conservation projects for candidate, proposed, and listed species. The most current Management Plan for Atlantic sturgeon was written by Taub (1990) and contains recommendations for increasing populations, but this plan is outdated and will likely be superseded by a Recovery Plan as required by the Endangered Species Act.

6.1.4 Past Trends

The Delaware River historically supported the largest population of Atlantic sturgeon in the United States. A historical reconstruction produced an estimated stock size large enough to include 180,000 mature females, exceeding estimated abundances of all other Atlantic sturgeon stocks by an order of magnitude (Secor 2002). In 1897, 978 fishermen, 80 shoresmen, and 45 transporters were engaged in the Delaware River sturgeon fishery (Cobb 1899). This heavy fishing in the late nineteenth century caused a severe stock decline. It is clear that Atlantic sturgeon underwent significant range-wide declines from historical abundance levels due to overfishing in the late 1800s (U.S. Departments of Commerce and Interior 1998). During the season of 1898, New Jersey fishermen caught 5,060 sturgeons valued at $19,375 and they prepared 1,067 kegs of caviar valued at $76,861. This does not include the catch from Delaware and Pennsylvania since their sturgeon fisheries were not canvassed that year (Cobb 1899).

Due to their migratory nature, high age to maturity, high longevity, and variable spawning periodicity, it is difficult to assess the size of Atlantic sturgeon populations using traditional fishery methods such as mark-recapture. Therefore, there are no detailed past population trends available other than the large decline in harvest levels mentioned previously from the late 19th century to levels in the mid-late 20th century when commercial harvest was still permitted. After the late 1800's, Atlantic sturgeon populations did not rebound to any appreciable extent in the Delaware, as evidenced by the average annual landings of only 897 pounds during the period from 1980 – 1987 (Taub 1990). Beginning in the first half of the twentieth century, the complete lack of oxygen in the Delaware River during the warmer months in the Philadelphia to Wilmington reach made it impossible for the native Delaware River stock to recover. Atlantic sturgeon have been described as more sensitive to oxygen levels than rainbow trout. This reach of the River may have included the spawning grounds, which have not been determined precisely to this day, and certainly included the nursery grounds for young sturgeon.

Brundage and Meadows (1982) compiled records of Atlantic sturgeon captured in the Delaware River and Bay from 1958-1980 and found that out of the 130 reported captures, none were in spawning condition and most were sub-adults (less than the minimum size for sexual maturity). They were most abundant in the Delaware Bay (rkm 0-55) in the spring and in the lower tidal river (rkm 56-127) in the summer.

Historic habitat for Atlantic sturgeon in the Delaware River has been significantly altered. Large-scale dredging to accommodate commercial shipping traffic has changed substrate composition and tidal flows (Di Lorenzo et al. 1993; Walsh 2004). Within the period 1877 – 1987, the mean depth of the Delaware River increased by 1.6m and the mean cross-sectional area increased by nearly 3,000 m^2 (Walsh 2004). By 1973, USACE estimated that nearly 154,000,000 m^3 of material had been removed from the Delaware Estuary (Walsh 2004). The channel deepening process increased the tidal range in the Upper Estuary; simultaneously, extensive water removals and diversions were occurring within the nontidal watershed, resulting in saltwater intrusion in the freshwater-tidal reach of the Estuary.

6.1.5 Future Predictions

The ongoing sampling efforts of the DE DFW have documented successful sturgeon reproduction in recent years. Assuming this reproduction continues, the stock should grow and potentially could develop exponential growth, which occurred with the Delaware River spawning stock of striped bass (Kahn et al. in press). There are some potential limiting factors, which must be considered, however.

One critical factor is dissolved oxygen. In the last two decades, hypoxia has become more frequent than in the decades immediately prior, to the surprise of biologists monitoring the River (T. Fikslin, DRBC personal communication). There appeared to be a preliminary indication of little to no reproduction in years with the lowest dissolved oxygen (Kahn and Fisher 2012). This analysis should be updated. The DRBC has determined that future increases in minimum levels of dissolved oxygen could be achieved as suggested earlier (Ad Hoc Task Force 1979) by reducing the biochemical oxygen demand due to nitrogen, and that could be done by increased aeration of solutions prior to discharges from industrial and sewage treatment facilities, primarily due to increased oxidation of ammonia, which could be accomplished without extreme costs.

Commercial and industrial activity could limit the growth of the Atlantic sturgeon population in the Delaware River, but effective regulation of pollution could counteract negative effects. Since large sub-adult and adult Atlantic sturgeon prefer deep water habitat, they are continually at risk of mortality due to ship strikes, because the deepest portions of the Delaware River are typically in the shipping channel. Increased shipping traffic and introduction of larger ships will likely increase the risk of ship strike mortalities for large sub-adult and adult fish. Between 2005 and 2008, a total of 28 Atlantic sturgeon mortalities were reported in the Delaware Estuary. Sixty-one percent of the mortalities reported were of adult size and 50% of the mortalities resulted from apparent vessel strikes. For small remnant populations of Atlantic sturgeon, such as that of the Delaware River, the loss of just a few individuals per year due to anthropogenic sources of mortality such as vessel strikes may continue to hamper restoration efforts. An egg-per-recruit analysis demonstrated that vessel-strike mortalities could be detrimental to the population if more than 2.5% of the female sturgeon are killed annually (Brown and Murphy 2010).

Even though dredging of the tidal Delaware River will likely continue as maintenance dredging and for increasing channel depth to accommodate larger ships, updated dredging windows have been developed by the Delaware River Basin Fish and Wildlife Management Cooperative (Co-op). Using known life history data, these dredging windows are formulated to reduce impacts on sturgeon and other fish from dredging and related activities and are currently being considered for implementation by the U.S. Army Corps of Engineers (USACE) in permitting dredging and related activities. To better characterize habitat use in the tidal Delaware River, Delaware River sturgeon researchers are continuing the use of acoustic tags on sturgeon to monitor their movements via an array of stationary acoustic receivers deployed in the Delaware River (Fig 6.1.2)

Since the Delaware stock was included in the populations listed as Endangered, a Recovery Plan for the species must be written that includes specific steps needed for population recovery. The Endangered Species Act also requires the designation of "critical habitat" for listed species when "prudent and determinable." Critical habitat includes geographic areas that contain the physical or biological features that are essential to the conservation of the species and that may need special management or protection. Critical habitat designations affect only Federal agency actions or federally funded or permitted activities. Federal agencies are required to avoid "destruction" or "adverse modification" of designated critical habitat. Relative to the Delaware River Atlantic sturgeon, this would apply to dredging activities which are currently permitted by the USACE in areas known to be utilized by Atlantic sturgeon for completion of their life cycle. Critical habitat may include areas that are not occupied by the species at the time of listing but are essential to its conservation. An area can be excluded from critical habitat designation if an economic analysis determines that the benefits of excluding it outweigh the benefits of including it, unless failure to designate the area as critical habitat may lead to extinction of the listed species.

6.1.6 Actions and Needs

Specific research goals could yield information that would be valuable in managing the population towards recovery. Continuation of telemetry studies could result in discovering areas of the river used by various life stages of the species, such as locations of spawning areas and early life stage nursery areas. Such knowledge could allow more effective management actions, such as potentially instituting effective dredging windows to protect fish at times when they congregate in known areas. Expanded study of ship strikes on sturgeon in the Delaware River is also needed to determine the level of population impact occurring and to determine ways to minimize that impact. Since small losses of broodstock can impact Atlantic sturgeon population growth in the Delaware, it is important to work with the shipping industry to develop means for reducing ship strikes.

Figure 6.1.5 Atlantic sturgeon of near-adult size (6 feet total length) found washed up in front of Baker's Bay Condominiums, PA (rkm 181) on June 12, 2010. This sturgeon has a propeller strike that runs laterally along the dorsal side of the fish through 5 dorsal scutes and the cranial area. Photo credit: Delaware Division of Fish and Wildlife.

Since the species is highly migratory, actions to rebuild the Delaware River stock could include: (1) reducing by-catch from near-shore and ocean commercial fisheries on the East Coast by increasing the number of observers on commercial fishing vessels and reducing the use and/or soak time of anchored gill nets, (2) designing and locating future tidal turbines for power generation in a manner which would strive to minimize mortality to distant migrants, and (3) continuing the use of the Coastal Sturgeon Tagging Database as a means to promote data sharing between sturgeon researchers. Kahn and Fisher (2012) presented evidence that the hypoxia occurring in and near the possible spawning areas and the known nursery areas of the River in recent years may be causing mortality of young-of-year sturgeon; the DRBC should raise the minimum criteria for dissolved oxygen in the River to reduce or eliminate this potentially devastating mortality that could be wiping out entire year classes of Atlantic sturgeon.

6.1.7 Summary

In summary, the current abundance of the Atlantic sturgeon population in the Delaware River is lower than the historic peak population prior to the late 19th century. The Delaware River spawning stock, once the largest on the Atlantic coast, was declared Endangered in 2012. Furthermore, shipping traffic in the Bay and River is causing some mortality by ship strikes. However, a recent peer-reviewed estimate of the abundance of juveniles in the River ranges between 2,000 and 33,000 fish (Hale et al. 2016). This is positive evidence of ongoing reproduction in the Delaware. Research is producing increasing information on habitat choice based on acoustic transmitters. Over the last decade and a half, dissolved oxygen levels in the River have sometimes dropped to levels of concern in summer, when young sturgeon are the most vulnerable (Kahn and Fisher 2012). This species has been described as more sensitive to dissolved oxygen than rainbow trout by one biologist. Increasing the "criteria" for dissolved oxygen to reduce the frequency of hypoxia would protect young sturgeon from potential sporadic mortality.

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Suggested Citation for this Chapter

Kahn, D. M. 2017. "Chapter 6.1 - Atlantic Sturgeon" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 215-226.

6.2 Blue Crab

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6.2.1 Introduction

The blue crab (*Callinectes sapidus;* Fig 6.2.1) is a member of the swimming crab family Portunidae and inhabits estuarine habitats throughout the western Atlantic, from Nova Scotia (although rare north of Cape Cod), along the Gulf of Mexico and Caribbean, to northern Argentina, and along western South America as far south as Ecuador (Williams 1979).

Figure 6.2.1 Adult Blue Crab. Photo credit: LeeAnn Haaf, Partnership for the Delaware estuary.

Blue crab spawning occurs primarily in the summer months in mid to lower Delaware Bay with peak larval abundance occurring in August (Dittel and Epifanio 1982). Larvae are exported from the Estuary into the coastal ocean where they undergo a 3-6 week, seven stage, zoeal development period in surface waters (Epifanio 1995; Nantunewicz et al. 2001). Models describe an initial southward transport of zoeae along the inner continental shelf within the buoyant estuarine plume after exiting the Estuary (Epifanio 1995, Garvine et al. 1997). Northward transport back toward the Estuary is provided by a wind-driven band of water flowing northward along the mid-shelf. Across-shelf transport into settlement sites in Delaware Bay is accomplished by coastal Ekman transport tied to discrete southward wind events (nor'easters) in the fall. These discrete wind events may have a large effect on larval recruitment and settlement success in the Bay and strongly influence year class strength.

Females mate immediately after their pubertal molt into sexual maturity, usually late in their first year of life (late spring, summer). Sperm is stored over their remaining lifetime from this single mating event. Mated females can begin producing eggs in that summer and early fall over multiple clutches, continuing through to a second spawning season (Churchill 1921; Van Engle 1958; Darnell et al. 2009). Darnell et al. (2009) observed up to seven clutches for females in North Carolina. Prager et al. (1990) estimated fecundity per batch as over $3x10^6$ eggs.

Blue crabs hold an important ecological role as opportunistic benthic omnivores, with major food items including bivalves, fish, crustaceans, gastropods, annelids, nemertean worms, plant material, and detritus (Guillory et al. 2001). Post-settled blue crabs have been shown to have a key effect on infaunal community structure, particularly through major predation on bivalves such as the eastern oyster (*Crassostrea virginica*) (Eggleston 1992), quahog (*Mercenaria mercenaria*)(Sponaugle and Lawton 1990), common rangia (*Rangia cuneata)* (Darnell 1958), soft-shell clam (*Mya arenaria)*(Blundon and Kennedy 1982; Smith and Hines 1991; Eggleston et al. 1992), and other bivalve species (Blundon and Kennedy 1982), and through indirect mortality on infaunal species from mechanical disturbance of sedimentary habitats caused by foraging (Virnstein 1977).

The primary predators on blue crabs appear to be fish, with more than 60 known fish predator species (Guillory et al. 2001). Blue crabs are known to be a common component of both juvenile and adult striped bass in Chesapeake Bay, albeit with great variability in relative importance among studies (Speir 2001). Although there have been recent investigations on the potential negative effect of the recovered striped bass stock on the Chesapeake Bay blue crab stock, no connection with decreasing blue crab population numbers has been supported (Booth and Martin 1993; Speir 2001).

Another very important source of predation on blue crabs occurs from cannibalism, as blue crabs make up as much as 13% of the diet (Darnell 1958). Cannibalism appears to increase with increasing crab predator size and is heaviest during the period of juvenile recruitment (Mansour 1992). Adult predation may be a key factor in density-dependent regulation of juveniles (Peery 1989).

Overfishing and stock sustainability became serious concerns during a period of rapidly rising fishing effort and three-fold increase in landings from 1985-1995. Fears of overfishing intensified after bay-wide landings from Delaware and New Jersey peaked at a record 12.7 million pounds in 1995 and then subsequently dropped by more than 46% in 1996.

Concern for the stock in 1998 prompted the 138th General Assembly of the State of Delaware to direct its Division of Fish and Wildlife to prepare a fishery management plan and quantitative assessment of the stock. Subsequent stock assessments revealed high fishing mortality rates in Delaware Bay in close proximity to the management threshold (fishing mortality F=1.3) suggesting that the stock was fully exploited (Helser and Kahn 1999; Wong 2010).

6.2.2 Description of Indicator

Perhaps the most-studied fishery species in Delaware, the blue crab has been very closely monitored since 1978 with monthly trawl surveys conducted by the Delaware Division of Fish and Wildlife (DE DFW). Using biological information collected from these surveys, together with year-round collections of landings reports, the DE DFW assesses the size and status of the Delaware Bay blue crab stock on an annual basis. This annual stock assessment is funded by the National Atmospheric and Oceanic Administation (NOAA).

6.2.3 Present Status

The blue crab stock in Delaware Bay supports a multi-million dollar fishery. Over 6.2 million pounds were landed in 2015 (most-recent data) in the bistate fishery in Delaware Bay, roughly equal to the 43-year average (6.4 million pounds) (Fig 6.2.2), with a dollar value at dockside of $12 million. Annual Delaware Bay harvest is generally split equal between the two States (51%:49%, DE:NJ).

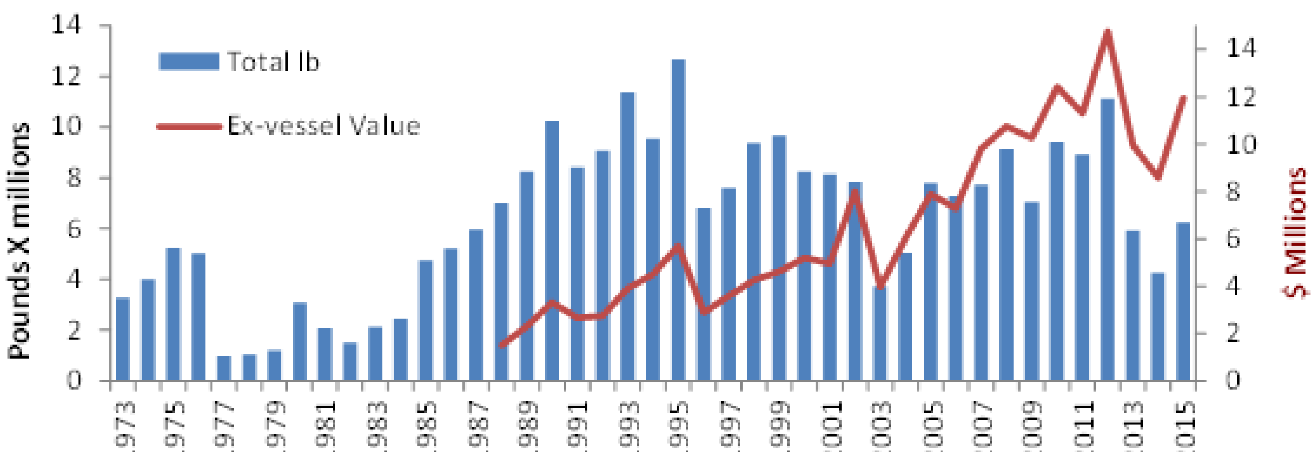

Figure 6.2.2 Total commercial and recreational landings (in pounds, lb) and commercial ex-vessel value in the States of Delaware and New Jersey.

In the State of Delaware, the blue crab is by far the most important and valuable commercial fishery. Its annual landings in weight are typically 50% greater than the combined landings of all other Delaware fisheries. Its ex-vessel value in dollars nearly triples the value of all other fisheries combined (Wong, unpublished).

The blue crab is the most heavily harvested recreational fishery species in Delaware Bay, exceeding 2 million crabs annually (Wong, unpublished). Recreational harvest accounts for about 3% and 15% of the total landings in Delaware and New Jersey, respectively.

The pot fishery, by far, harvests the majority (86%) of Delaware's crab landings and value (Fig 6.2.3). Male crabs make up about 2/3 of the pot landings, in stark contrast to the female-dominated winter dredge fishery landings (Fig 6.2.4).

Stock Size and Status The Delaware Bay blue crab stock is currently at healthy levels of abundance and at safe levels of fishing mortality. Population modeling indicates that the stock has recently risen to 174 million crabs, above the 38 year mean and median of 153 and 116 million (Fig 6.2.5) (Wong, unpublished). Fishing mortality rates are at levels below overfishing thresholds after declining appreciably since 2012.

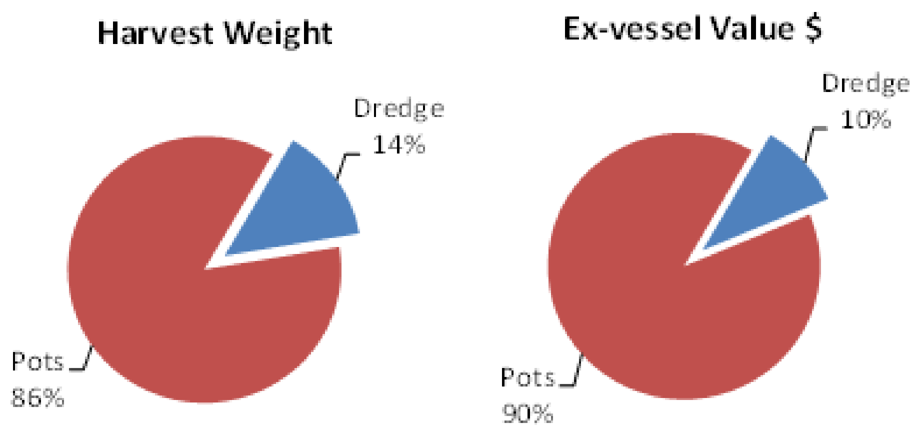

Figure 6.2.3 Total harvested weight and ex-vessel dollar value by gear type over the most-recent five years of Delaware landings data.

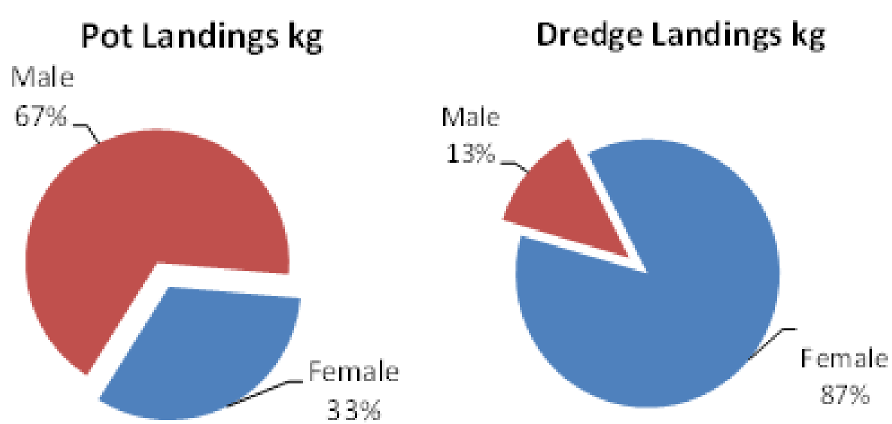

Figure 6.2.4 Sex-composition of pot and dredge fishery landings over the most-recent five years of Delaware landings data.

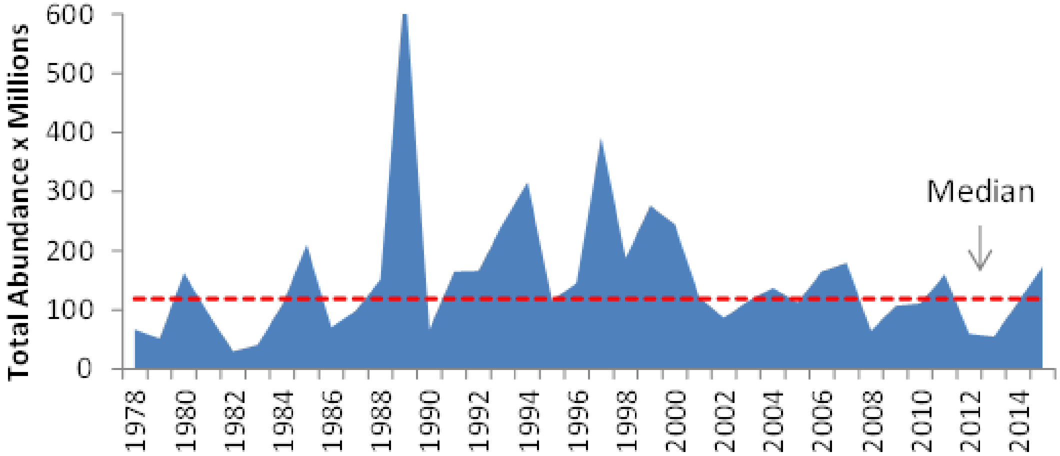

Figure 6.2.5 Stock size estimates from annual population modelling (Wong unpublished).

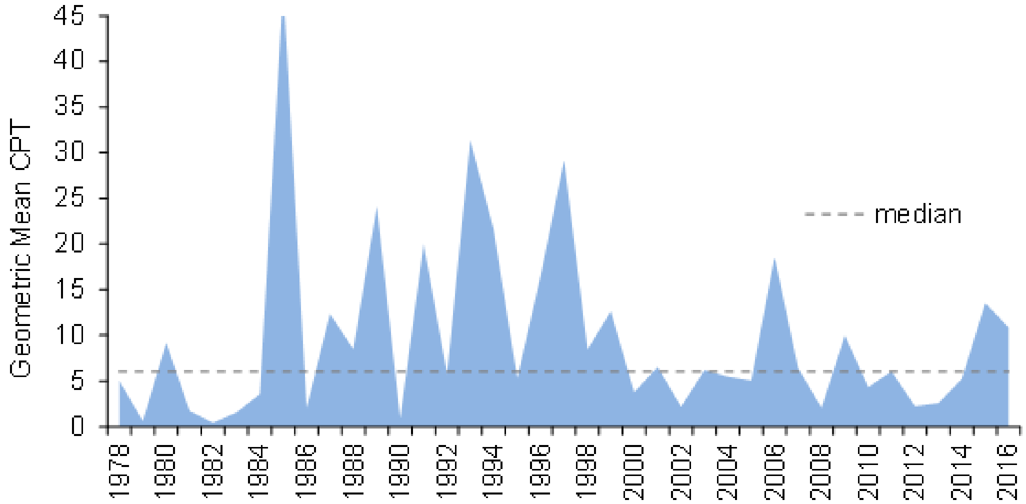

Figure 6.2.6 Young-of-the-year blue crab relative abundance from the DE DFW Delaware Bay trawl survey.

6.2.4 Past Trends

A period of high blue crab productivity occurred for about 15 years from 1985 to 1999 (Fig 6.2.6). During this period, DE DFW crab indices were at or above median levels for 13 of 17 years. Weak year classes occurred in 2000 and 2002, beginning a prolonged 15 year period of lower juvenile recruitment. In 2015 and 2016, the DE DFW has observed robust juvenile recruitment, perhaps signaling an end to this current low productivity period.

6.2.5 Future Predictions

The near-term outlook for the stock and fishery is promising given robust juvenile recruitment in 2015 and 2016. Young-of-the-year (YOY) recruitment is typically a good predictor of future fishery landings (Wong, unpublished) (Fig 6.2.7). With ostensibly warming water temperatures in the future, stock productivity could increase through a broadening of the spawning season and an increase in the number of egg clutches per year.

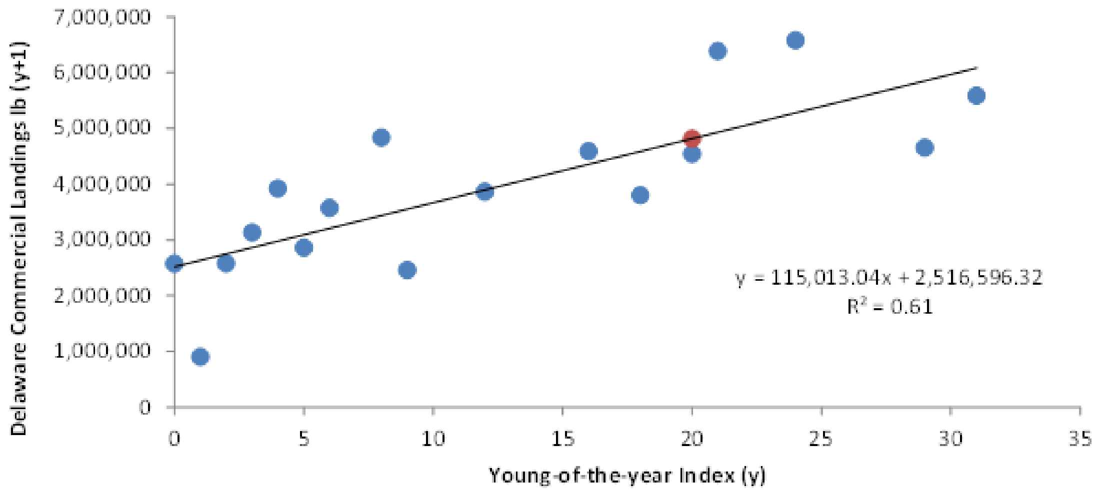

Figure 6.2.7 YOY abundance as a predictor of ensuing Delaware commercial landings.

6.2.6 Actions and Needs

Continued close monitoring of stock abundance through monthly trawl surveys and accurate reporting of fishery landings are needed to protect and manage this important fishery stock.

6.2.7 Summary

In recent years, from 2005 to 2012, high levels of exploitation rates were observed, driven by poor recruitment and below average stock abundance. However, after bottoming in 2012, juvenile recruitment has rebounded substantially, rising to above-average levels in 2015 and 2016. Low levels of harvest from 2013 to 2015 have allowed adult abundance to climb to its highest level in 16 years. Population modelling indicates that the total stock has risen to 174 million crabs, above 38 year norms (Wong, unpublished). Consequently, fishing mortality rates have declined appreciably, existing at levels safely below overfishing thresholds. The Delaware Bay blue crab stock is currently at healthy levels of abundance, and at safe levels of fishing mortality. The near-term outlook is promising given robust juvenile recruitment in recent years.

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Suggested Citation for this Chapter

Wong, R. 2017. "Chapter 6.2 - Blue Crab" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 227-232.

6.3 Osprey

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6.3.1 Introduction

One of the largest birds of prey in North America, the osprey (*Pandion haliaetus;* Figure 6.3.1) eats almost exclusively fish, which makes up 99% of their diet. Osprey are found on all continents except Antarctica, generally near large bodies of water. Ospreys arrive in Delaware Bay in early March and begin nesting by mid March. They use a variety of nest sites including: live or dead trees, man-made nesting platforms, utility poles/structures, channel markers, and duck blinds. Young fledge in the early summer. Wintering occurs in the Caribbean, Central America and South America.

Osprey are highly adapted for capturing fish. Some of their adaptations include: oily feathers to reduce water absorption, spikes on their feet to aid in grasping slippery fish, and a reversible outer toe helping them keep a secure grip on fish. At times osprey may plunge completely underwater in pursuit of their prey. Bald eagles (*Haliaeetus leucocephalus*) and great horned owls (*Bubo virginianus*) are known to take fledgling osprey. Raptors and other birds will take over osprey nests. Bald eagles are well known to rob osprey of the fish they have caught.

Figure 6.3.1 Adult Osprey diving talons first to catch fish prey. Photo credit: Lenni Gabriele.

6.3.2 Description of Indicator

Both New Jersey and Delaware have osprey monitoring and conservation programs. Nest checks by aerial or ground observers are conducted by staff and volunteers to determine active nests and productivity between the end of April and mid-July. Each state works independently on their monitoring programs so timing and the survey areas are different (Delaware focused effort in Inland Bays until 2007 and New Jersey surveyed state-wide), and the reports upon which this indicator is based are produced independently (Figure 6.3.2).

6.3.3 Present Status

Ospreys appear to be doing well in Delaware Bay. Productivity, as measured by fledglings observed, is higher than needed for a stable population. Population levels may be close to what is believed to have been the level prior to the widespread use of Dichlorodiphenyltrichloroethane (DDT). A recent study by U.S. Geological Survey of osprey nesting in Delaware concludes that contaminants are below levels that would cause concern.

Table 6.3.1 Osprey nesting success during 2003, 2007, and 2014 in Delaware.

	2003	2007	2014
Active Nests in DE	119	173	197
Successful Nests in DE	77	136	103
Nestlings	135	293	424

Active Nest = eggs or chicks seen in nest during at least 1 survey
Successful Nest= at least one chick reach banding age

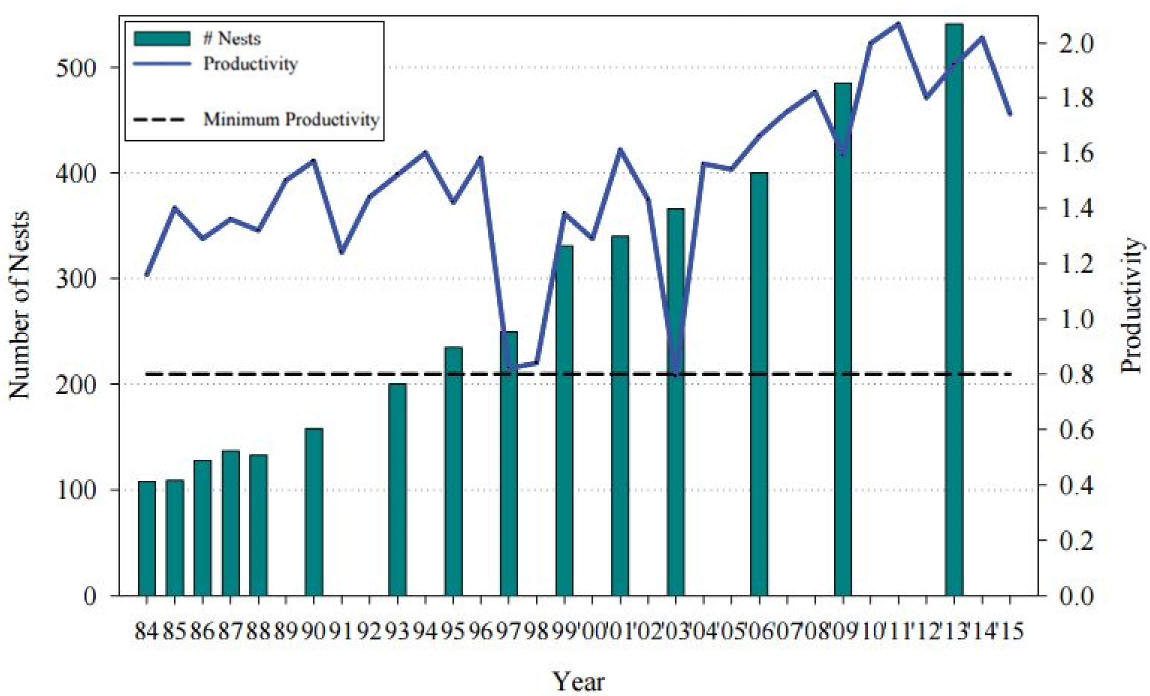

Figure 6.3.2 Osprey nesting population (bar) and productivity in terms of young fledged per nest (heavy line) 1984-2015 in New Jersey.

6.3.4 Past Trends

Historically abundant, osprey populations declined precipitously in the Northeast from the 1950s through the 1970s, due to the widespread use of DDT to control mosquitoes. Since DDT was banned, osprey populations have been slowly rebuilding, aided by reintroduction programs. Delaware Bay populations remained depressed due to high organochloride and polychlorinated biphenyl (PCB) levels into the 1990s. Since then, levels of organochlorides have lowered and productivity has improved.

6.3.5 Future Predictions

The outlook for osprey is good in Delaware Bay. Disturbance is generally not an issue, they adapt well to anthropogenic activities. Contaminants have been reduced and levels in osprey continue to decline. Expectations are that osprey will continue to show success in Delaware Bay.

6.3.6 Actions and Needs

Volunteers are needed for monitoring nests and productivity. Since osprey readily use artificial platforms and structures for nesting, those interested in establishing nesting structures, or that have questions about osprey should contact the State agencies responsible for bird conservation:

NJ: http://www.conservewildlifenj.org/protecting/projects/osprey/

DE: http://www.dnrec.delaware.gov/fw/NHESP/information/Pages/Contacts.aspx

6.3.7 Summary

Osprey populations in Delaware Bay are a success story. They demonstrate the value of reducing contaminants in our environment and taking conservation actions. In addition, the success of osprey conservation shows how volunteers can make a difference.

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Suggested Citation for this Chapter

Breese, G. 2017. "Chapter 6.3 - Osprey" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 233-235.

6.4 White Perch

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6.4.1 Intoduction

White perch (*Morone americana;* Fig 6.4.1) are one of the most abundant fish in the Delaware Estuary and probably the most widespread, found in nearly all the waters of the Delaware Estuary, from the lower bay to uppermost reaches of the Estuary's many tidal tributaries. White perch support important recreational and commercial fisheries throughout the Estuary. The Delaware Estuary white perch population is currently in good condition and is not overfished.

Figure 6.4.1 White Perch. Photo credit: Jenny Paterno Shinn.

White perch are closely related to striped bass, but the white perch is a much smaller fish. Although the Delaware state record white perch was 2 pounds 9 ounces, any white perch over one pound is considered large. Delaware Estuary white perch display anadromous tendencies in that large aggregations of white perch move into the tidal tributaries in spring to spawn and then out into the deeper waters of the Estuary to overwinter, but, unlike striped bass, white perch rarely leave the Estuary. White perch numbers in the Delaware Bay and River typically increased during the fall and remained high through winter, then decreased during the spring and summer (Miller 1963, PSEG 1984), while white perch numbers in the tidal tributaries showed the opposite trend (Smith 1971). However, white perch were caught year-round in both the Delaware Estuary (de Sylva et al 1962) and the tidal tributaries (Smith 1971), so the evidence was inconclusive about the extent of white perch movements. In addition, landlocked white perch populations have thrived for years in most of the freshwater ponds in the headwaters of Delaware Estuary tidal tributaries (Martin 1976).

White perch spawn in the Delaware River (Miller 1963, PSEG 1984) and most of the Delaware Estuary tidal tributaries (Miller 1963, Smith 1971, Clark 2001). Spawning occurred from early April through early June, but May was usually the peak spawning month (Miller 1963, Smith 1971, PSEG 1984). Young-of-the-year white perch, like the adults, were found in both the Delaware Estuary (PSEG 1984) and the tidal tributaries (Smith 1971). Young-of-the-year white perch were found throughout the year in the lower salinity reaches of all sampled tidal tributaries (Clark 2001).

White perch feed almost exclusively on small invertebrates from their larval through juvenile stages, and then add fish to their diet as they reach maturity (PSEG 1984). Almost all male white perch are sexually mature in two years and almost all female white perch are sexually mature in three years (Wallace 1971). Delaware Estuary white perch have been aged to ten years old and some may live longer than that, but white perch older than six years old were rare (Clark 2001).

White perch tolerate a wide range of environmental conditions, as would be expected of such a ubiquitous fish. White perch were caught at water temperatures ranging from 2.2° C (Rohde and Schuler 1971) to 35.5° C (Clark 1995) and at salinities ranging from freshwater (Shirey 1991) to 35 parts per thousand (Clark 1995). White perch catch per unit effort was greatest in fresh and oligohaline waters of Delaware tidal tributaries (Clark 2001), suggesting that white perch preferred low salinity water. Smith (1971) caught white perch at a dissolved oxygen level of 2.2 parts per million (ppm) in Blackbird Creek and Clark (1995) caught white perch at a dissolved oxygen level of 2.0 ppm in a high-level tidal impoundment near the Little River, but neither report indicated whether the fish showed signs of stress at those low dissolved oxygen levels.

White perch were among the top five finfish species landed commercially in Delaware during each year of the last decade, which is not surprising since gourmets consider the white perch to be one of the finest tasting fish in the world. Landings averaged 77,868 lbs during 2010 through 2015, with the highest landings, 157,947 lbs, reported in 2011. Most fishing effort for white perch was expended during late fall through winter and into early spring. Delaware Bay was the source for most commercially-caught white perch, but substantial landings also came from the Delaware River and several tidal tributaries of the Delaware Estuary. New Jersey white perch landings in the Delaware Estuary counties (Salem and Cumberland) averaged 24,333 lbs per year during 1995 through 2000, with the highest landings, 42,000 lbs, reported in 2000.

White perch were among the top ten fish species harvested recreationally in Delaware annually since 2000. The mean estimated recreational harvest during 2000 through 2015 was 36,311 pounds, with the highest harvest, 97,789 pounds, reported in 2010.

6.4.2 Description of Indicator

This indicator uses the white perch young-of-the-year (YOY) index derived from the Delaware Division of Fish and Wildlife's (DE DFW) Juvenile Finfish Trawl Survey. The juvenile finfish trawl survey used a 16' trawl to sample 39 inshore Delaware Bay and River stations monthly during April through October. The YOY index was calculated as the geometric mean number of YOY white perch caught per tow by the juvenile finfish trawl survey during June through October in Delaware Bay and River (Greco 2016). This index is an indicator of year-class strength and may indirectly be an indicator of future spawning stock abundance. For this index, the median value from 1990 through 2016 was 0.26 YOY white perch per tow (Fig 6.4.1). During four of the five years from 2012 through 2016, the annual index was below the median. Although the white perch YOY index has not been used as a predictor of future spawning stock abundance or future commercial catches, the low YOY index values of the last five years may be a factor in the decrease in commercial landings reported during 2013 through 2015.

6.4.3 Present Status

The fact that the white perch YOY index was below the time series median YOY index value during four of five years since 2012 suggests that the Delaware Estuary white perch spawning population has had poor spawning success during this period. Delaware white perch commercial landings exceeded 100,000 lbs. in 2009, 2010, and 2011, which is the only time landings have exceeded 100,000 lbs. for three consecutive years in the 1951 through 2010 time series. Landings have since declined and were below the time series mean in 2015. This suggests the population has declined since its recent high level.

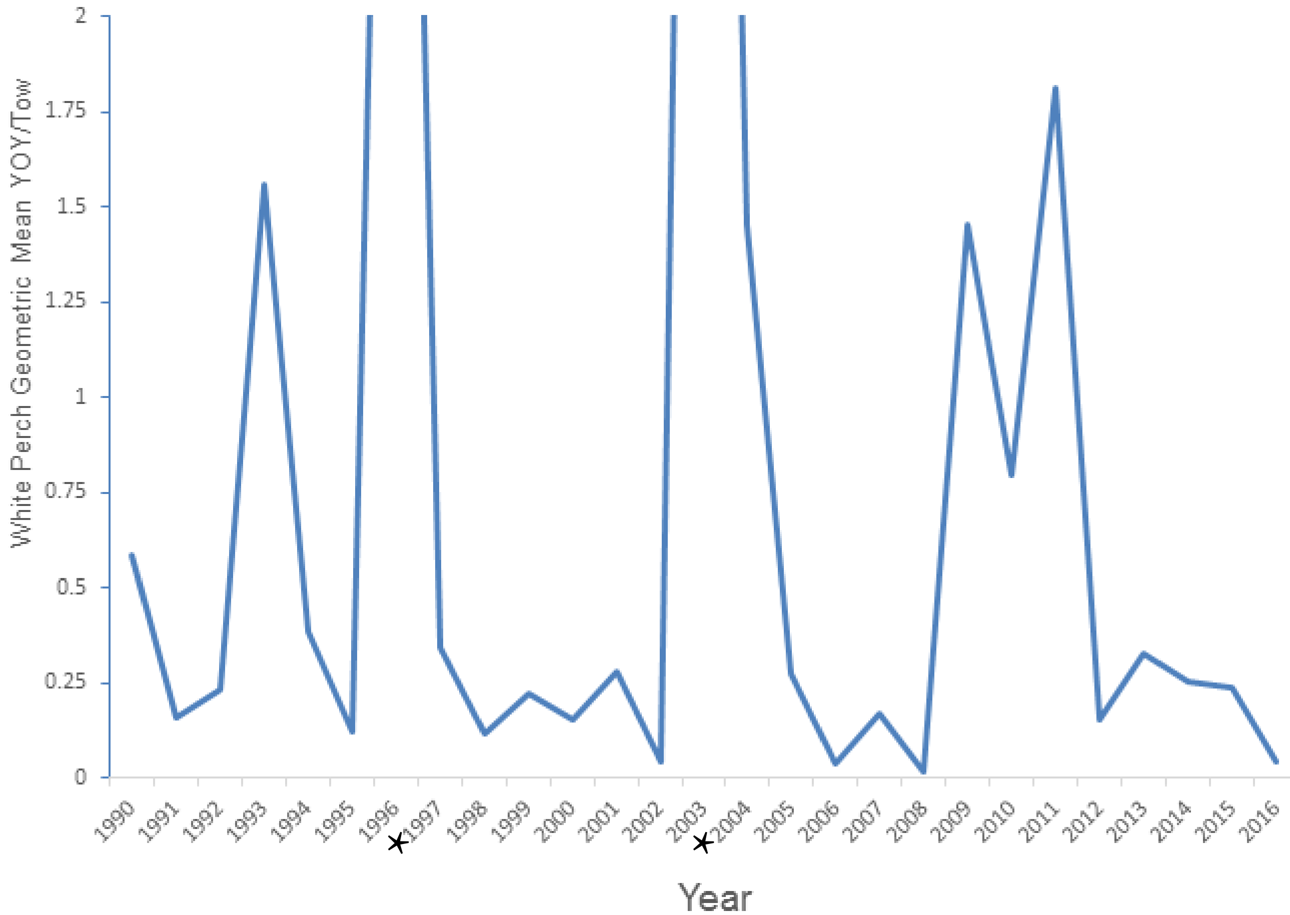

Figure 6.4.2 White perch YOY index (number of YOY white perch caught per trawl tow) from the DE DFW Juvenile Trawl Survey for 1990 through 2016. Index scale was truncated to better show index values around median. The 1996 value was 4.84 and the 2003 value was 6.35.

6.4.4 Past Trends

Delaware white perch commercial landings were the longest time series of data available to assess past trends in white perch abundance (Fig 6.4.3), but white perch landings were affected by several factors other than the white perch population, such as fishing effort, conditions during the fishing season, gears used, etc. Delaware white perch landings were high for several years during the 1950s, were low during most of the 1960s and 1970s, rose during the 1980s, and were near or above the time series mean during the 1990s through 2015. While Delaware's precipitous decline in commercial landings since their historic peak in 2011 may be the result of poor fishing or market conditions during the following years, it may also be a result of poor recruitment to the fishery during this time as suggested by the low YOY index during 2012 through 2016. Both the YOY index and the commercial landings suggest that the Delaware Estuary white perch population undergoes cyclical expansions and declines.

6.4.5 Future Predictions

The white perch's ability to inhabit almost all waters of the Delaware Estuary may buffer it from some of the extreme population fluctuations seen in other species, but habitat protection, particularly for areas of the Estuary in which white perch spawn, is important for the continued viability of this fish. Past trends suggest that white perch will continue to support important commercial and recreational fisheries in the Delaware Estuary for the foreseeable future.

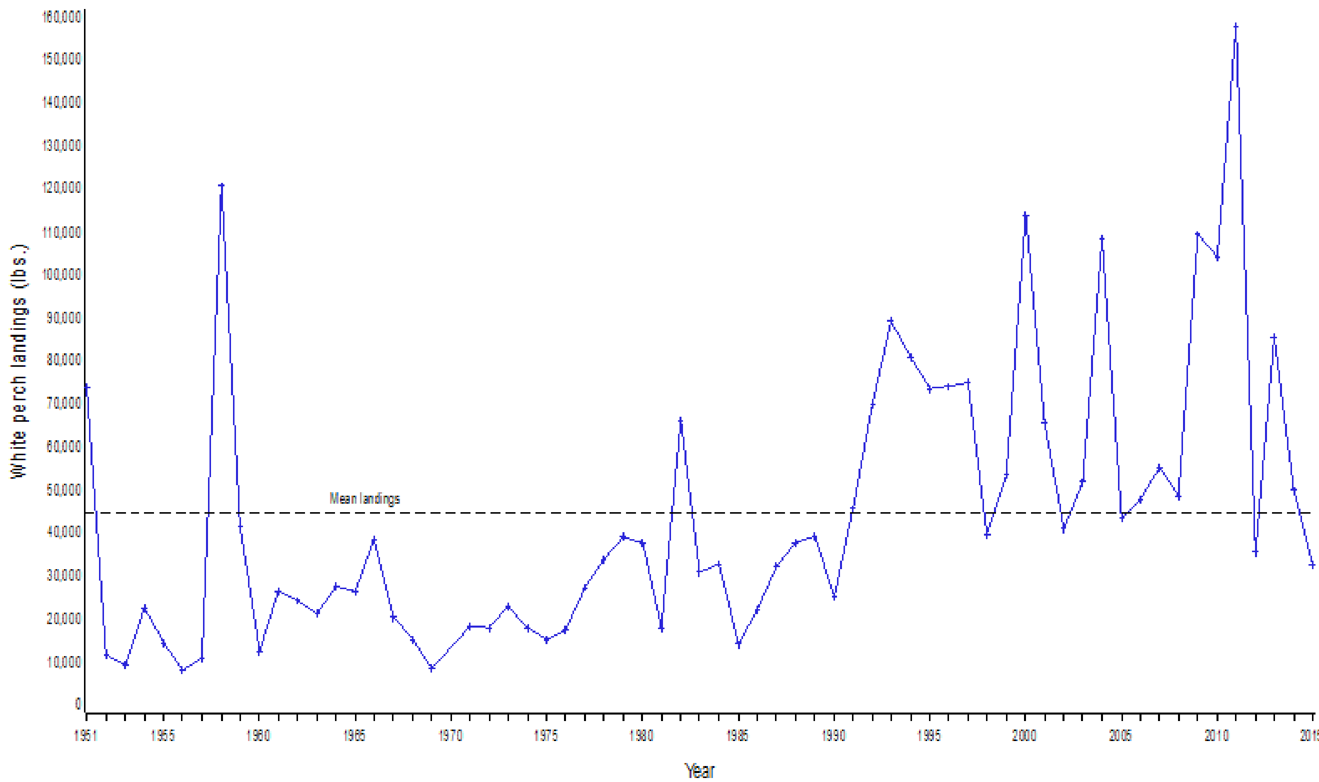

Figure 6.4.3 Delaware commercial white perch landings (lbs.) 1951 through 2015

6.4.6 Actions and Needs

The 8-inch minimum size limit for white perch, established by Delaware in 1995, has been effective in allowing almost all white perch to spawn at least once before recruiting to the fisheries. All states in the Delaware Estuary should establish an 8-inch minimum size for white perch to ensure that most white perch may spawn before they recruit to the fisheries.

White perch often spawn in areas of the Delaware River and in the upper reaches of Delaware Estuary tidal tributaries that have been subject to intense development pressure in the past 50 years. These are spawning habitats for many fish species, including white perch, and these habitats should be protected.

6.4.7 Summary

White perch are one of the most abundant and widespread fish in the Delaware Estuary. The species supports important commercial and recreational fisheries. Although the white perch population in the Delaware Estuary seems to be maintaining itself, some basic management measures will ensure the population continues to thrive.

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Suggested Citation for this Chapter

Clark, J. 2017. "Chapter 6.4 - White Perch" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 236-240.

6.5 Striped Bass

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6.5.1 Introduction

Striped bass (*Morone saxatilis*; Fig 6.5.1) are large, predatory fish of the family Moronidae with dark horizontal stripes extending from the opercula to the caudal peduncle. This species has been found to inhabit tidal creeks and rivers, jetties, beaches, and relatively open water in the Bay, River and ocean depending upon age and time of year. Striped bass are frequently referred to as rockfish because of a historic association with oyster reefs which were known as oyster rocks in the Mid-Atlantic region. Some younger, smaller individuals inhabit portions of the Delaware River Estuary year round, unlike other potentially large predators such as weakfish, bluefish, large sharks, and sea turtles which occur within the estuary seasonally. The Delaware Division of Fish and Wildlife (DE DFW), hereafter the Divsion, has conducted a survey to measure spawning stock biomass since 1996. Additionally, the Division has started to explore the use of acoustic telemetry to better identify migratory corridors and trends in habitat utilization. Preliminary results coupled with older tagging studies indicate that a large portion of the Delaware River spawning stock, primarily females, engage in a spring coastal migration to southern New England and eastern Long Island; mature females spawn in the River prior to migrating up the coast annually. However, male bass remain in the Estuary or nearby ocean waters year round. Further, the DE DFW has found evidence of exchange between the Chesapeake and Delaware Bays via the Chesapeake and Delaware Canal, indicating these fish use the canal as a migratory corridor between estuaries.

Figure 6.5.1 Adult Striped bass. Photo credit: Kurt Cheng, Partnership for the Delaware Estuary.

Once considered extirpated by some biologists prior to the improvement of dissolved oxygen (DO) levels in the 1980s, the Delaware River population is now one of the major spawning stocks on the Atlantic coast, along with the Hudson River and Chesapeake Bay stocks. Management action for striped bass can be traced as far back as pre-Colonial times, when use of striped bass for fertilizer was banned. The Delaware River spawning stock declined greatly by the mid-twentieth century, in response to frequent, prolongued periods of hypoxia and anoxia in the late spring through early fall in the spawning grounds from Philadelphia through Wilmington reaches (ASMFC 1981; Kahn et al., in press), with some areas having persistent DO concentrations at zero during the summer months in the 1950s and 1960s (Sharp 2010). The Delaware River oxygen content increased during the 1970s and 1980s due to the Clean Water Act, which produced pollution reduction and upgrades to the sewage treatment plants along the River. During the 1980s, production of striped bass young-of-year increased gradually with a large surge in 1989 (Fig 6.5.2). In 1998, the Atlantic States Marine Fishery Commission (ASMFC) declared the Delaware River stock recovered, based on a report by Kahn et al. (1998).

Striped bass feed on a number of fishes and invertebrates throughout their life cycle with a general increase in prey size concomitant with individual growth. Younger bass feed primarily on smaller invertebrates including zooplankton, insects, worms, and amphipods. However, juveniles will also feed on fish larvae and small pelagic fish species as growth and ontogeny progress. Larger bass have been found to predominately prey on small pelagic fish species such as anchovies, river herring, Atlantic silverside, and Atlantic menhaden (Griffin and Margraf, 2003) with secondary prey items including larger invertebrate species (e.g. blue crab, Atlantic rock crab, and American lobster; Pruell et al. 2003; ASMFC 2013).

Striped bass spawning grounds exist in tidal fresh water in the Delaware River generally above detectable concentrations of salinity. However, the DE DFW has observed spawning activity in nearby tidal waters with salinities ranging from 0.5 – 5.0 ppt. Similarly, a previous study demonstrated that bass successfully spawned within a narrow range of very low salinities (0.70-1.5 ppt) in the Chesapeake and Delaware Canal

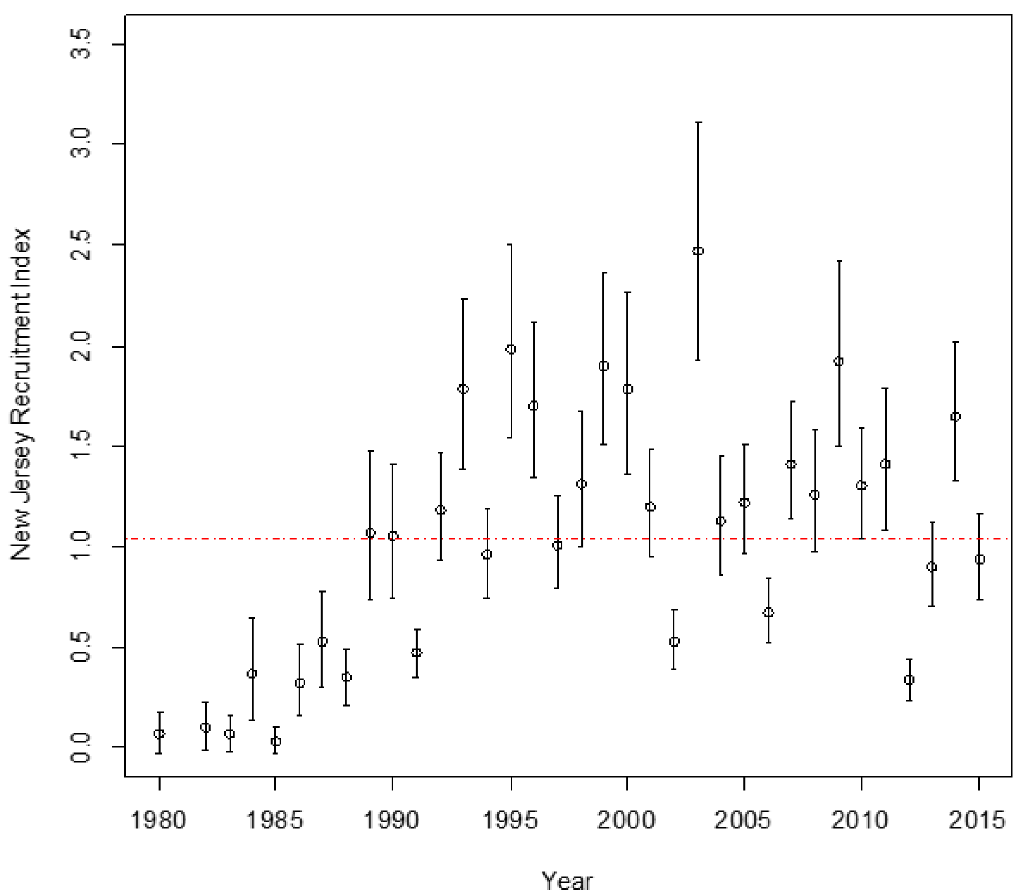

Figure 6.5.2 The annual Delaware River Recruitment Index, the geometric mean number of young-of-year bass caught per seine haul, with the time series mean shown by the red dashed line. Source: New Jersey Division of Fish and Wildlife.

(Johnson and Koo 1975; Greene et al. 2009). The Delaware spawning survey usually finds more fish in April in Delaware waters from the Delaware Memorial Bridge up to the Delaware-Pennsylvania line. However, the New Jersey shore is typically where the majority of spawners congregate, along with the Cherry Island Flats, which are shoals in the River opposite Wilmington. As the season progresses into May, the temperature and salinity tend to increase, and spawning bass are more commonly collected in Pennsylvania waters up to the Philadelphia Navy Yard. Spawning usually terminates by the end of May. By September, young-of-year bass are several inches long, and do not typically exceed four inches before November.

In addition to being integral to the ecology of the Estuary, striped bass are of economic benefit to both the State of Delaware and the State of New Jersey. Delaware has a commercial fishery targeting the species. Currently, this fishery has the highest economic value of any of Delaware's commercial fin fisheries and is second only to the commercial blue crab fishery in terms of total ex-vessel value in the state. In 2015, Delaware commercial fishers generated more than $550,000 in ex-vessel value from striped bass landings (Fig 6.5.3). However, the State of New Jersey has banned the commercial harvest of striped bass for decades. Despite the difference between the commercial activities of the two states, both Delaware and New Jersey have a large recreational fishery, which ranks as one of the most popular in both states. The species is one of a few inshore species that can achieve big game size, with occasional fish exceeding 50 pounds.

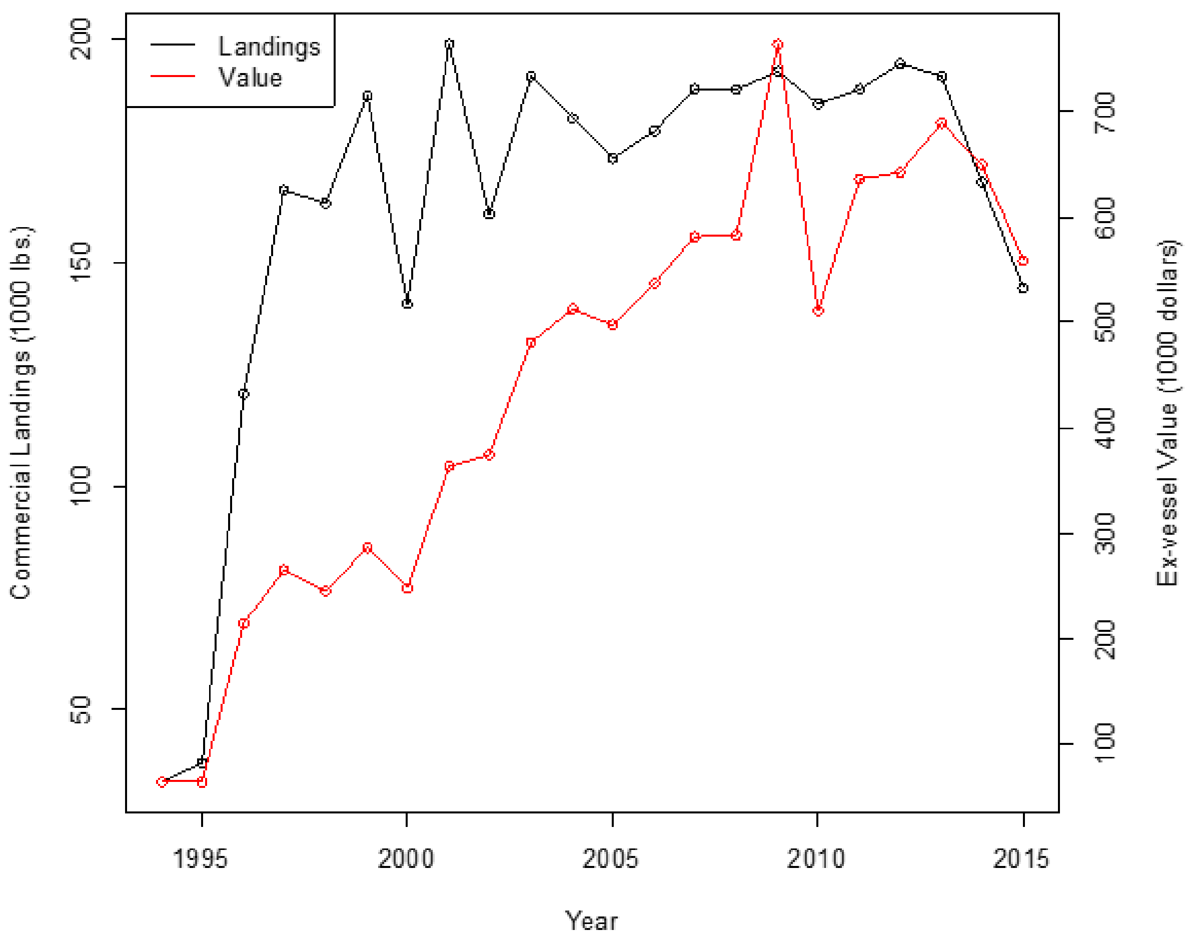

Figure 6.5.3 The total annual landings and ex-vessel value of commercially caught Striped bass in the State of Delaware.

6.5.2 Description of Indicator

Two indicators from the Delaware River Estuary serve to measure the relative health of the striped bass population: the Delaware Spawning Stock Survey and the New Jersey Recruitment Survey. Both surveys use a geometric mean to provide a quantitative annual index of two biological parameters to compare performance through time. The first index, a geometric mean of the number caught per unit of electrofishing effort on the spawning grounds in April and May, is a measure of the reproductively capable abundance of the stock (Fig 6.5.4). The second index, the geometric mean of the number of young-of-year bass caught per seine haul, is a measure of the annual reproductive output of the stock (Fig 6.5.2).

6.5.3 Present Status

Survival to age one varies annually in response to a multitude of factors, including but not limited to, adult spawning intensity, hydrodynamic properties, growth, quantity and quality of larval prey, and corresponding larval condition. A large year class at the young-of-year stage often results in a greater number of recruits into the fishery several years later. Regardless of the observed fluctuations between years, the overall status of the Delaware River spawning stock is positive suggesting that current management practices are sustainable.

6.5.4 Past Trends

Striped bass are presently harvested at sustainable levels along the Atlantic coast (ASMFC 2016). Improvements to water quality and a successful management regime are cited as the principle reasons for the dramatic improvement in the population. Within the Delaware River Estuary, the annual Spawning Stock Survey index has varied from 0.86 to a high of 4.10, with a mean of 2.34 from 1996-2015 (Fig 6.5.4). The index was generally higher from 1996-2005 compared to the period from 2005-2015. However, a great deal of inter-annual variability is present in the index.

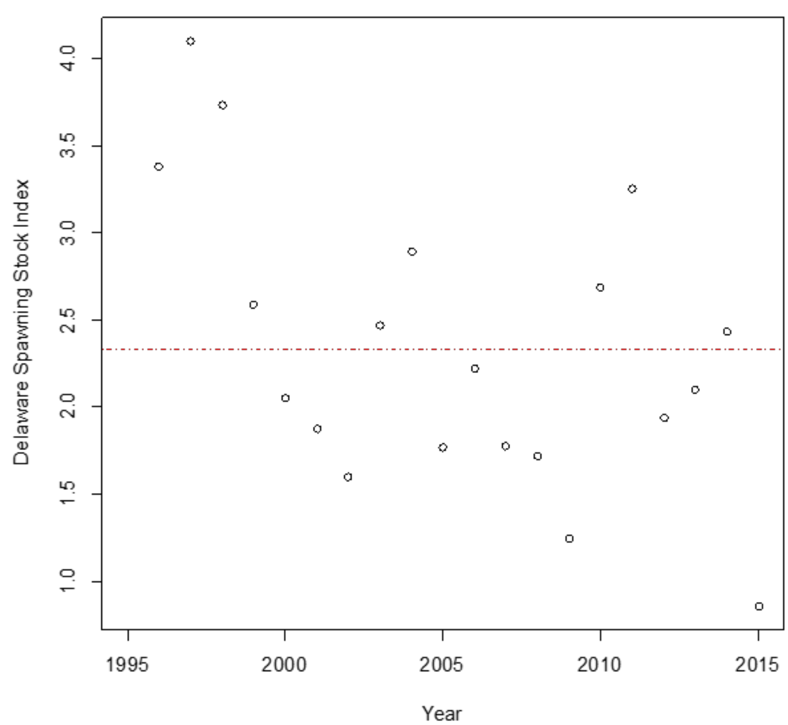

Figure 6.5.4 The annual Delaware Spawning Stock Survey index with the time series mean shown by the red dashed line.

The annual New Jersey Recruitment Survey index has ranged from 0.03 to 2.47, with a time series mean of 1.04 from 1980-2015 (Fig 6.5.2). Similar to the Spawning Stock Survey index, the recruitment index was below the time series mean in 2015, but above it in 2014 demonstrating substantial inter-annual variability. Further, the coast wide status of the stock was recently determined to be not overfished, nor was the stock currently experiencing overfishing relative to the biological reference points (ASMFC 2016).

6.5.5 Future Predictions

The striped bass fishery is managed under relatively conservative regulations to maintain high levels of spawning stock biomass. The current reference points were enacted to protect a coastwide spawning stock biomass target of 125% of the 1995 levels (the year the species was declared recovered by the ASMFC). When examining the number of striped bass caught per recreational trip in Delaware, a similar pattern of high inter-annual variability compared to the Delaware Spawning Stock Survey becomes apparent (Fig 6.5.5), demonstrating the inherent irregularity in annual harvest. Despite a lower value observed in 2015, the recreational catch per trip was generally higher in the last twenty years than the time series average suggesting that the species has been managed to maintain relatively high levels of productivity.

6.5.6 Actions and Needs

In order to ensure sustainable levels of future harvest, we need to continue monitoring long term trends in biomass and recruitment, responding when necessary with management action.

6.5.7 Summary

Striped bass are large, predatory fish that are important to the ecology of the Delaware River Estuary and the economy of the surrounding states. In response to conservative historical management measures and improved habitat availability and thanks to enhanced water quality conditions, the species has rebounded

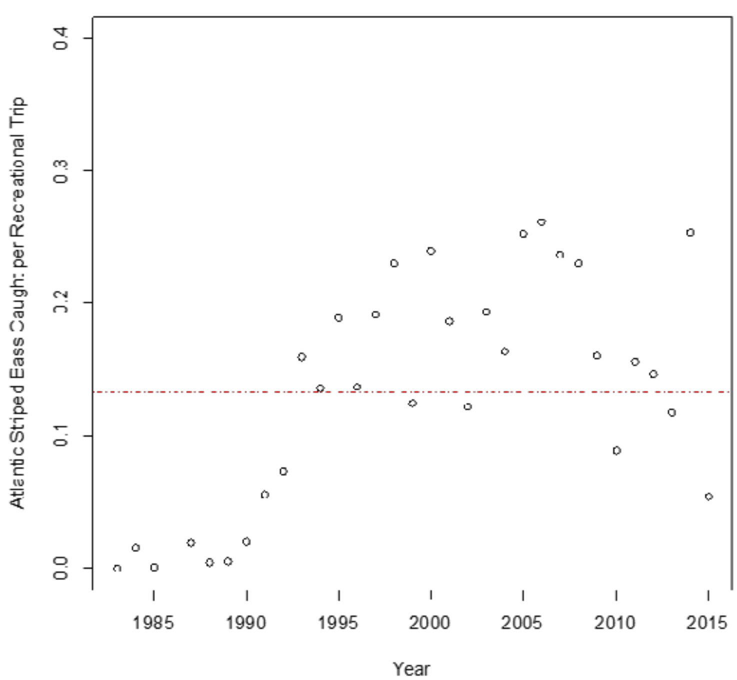

Figure 6.5.5 The annual index of recreationally caught Striped bass caught per trip with the time series mean shown by the red dashed line.

from historic lows to new highs in abundance. This stock has come to represent a significant management success and continues to provide a sustainable fishery resource. In order to continue to sustainably harvest striped bass, we will need to continue long-term monitoring programs and advance our mathematical modelling to better approximate the dynamics of an ever changing environment.

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Suggested Citation for this Chapter

Hale, E. 2017. "Chapter 6.5 - Striped Bass" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 241-246.

6.6 Weakfish

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6.6.1 Introduction

Figure 6.6.1 Weakfish landed in the Delaware Bay. Photo credit: Jenny Paterno Shinn.

Weakfish (*Cynoscion regalis;* Fig 6.6.1) is a marine fish that is member of the drum family Sciaenidae. Locally, weakfish often go by other common names such as grey trout or sea trout; although they are of no relation to the "true" trout family Salmonidae. Weakfish occur along the Atlantic coast from Nova Scotia, Canada to southeastern Florida, but are most common from New York to North Carolina. Weakfish once dominated Delaware's recreational and commercial landings in the 1970s and 1980s, and the species was named the Delaware State Fish in 1981. With the onset of spring and the warming of coastal waters, adult weakfish begin a northerly inshore migration from offshore waters off the Carolina coast to nearshore coastal waters and estuaries to spawn. Spawning in the Delaware Estuary occurs in the shallows and on shoals in the middle and lower Bay and generally begins in May with sporadic, secondary spawning taking place throughout the summer. Larger weakfish, over several pounds, which were extremely common in the 1970s and 1980s and less so in the later 1990s, spawn in the spring and then leave the Bay. These larger fish may then migrate to southern New England. Younger, smaller adult weakfish tend to stay in the Bay all summer, and could spawn more than once. From late spring through early fall, young-of-year weakfish are found throughout the Estuary from the lower Bay up into the Delaware River. In recent years, Age 0 weakfish have started to appear in surveys in mid to late June. Young weakfish are fast growing, often reaching a length of six- to eight-inches before leaving the Bay in the fall to migrate south as water temperatures decline.

Weakfish feed on a variety of prey ranging from invertebrates like crustaceans and mollusks to various fish species. Younger fish feed on mysid shrimp, also known as opossum shrimp, and sand shrimp, which can be very abundant in mats of grass detritus washed out of marshes. Larger weakfish are more piscivorous, feeding mainly on other fish, primarily members of the Clupeidae family like Atlantic Menhaden. Larger weakfish are also cannibalistic, feeding on young-of-year weakfish (Merriner 1975; Thomas 1971).

Weakfish abundance and catches have been declining coastwide since the late 1990s. A coastwide stock assessment completed in 2006 found natural mortality had increased beginning in 1996, eventually causing the stock to decline (ASMFC 2006). That assessment developed a hypothesis that predation and possibly competition from striped bass and spiny dogfish caused the large increase in natural mortality that led to the weakfish decline. Although coastwide young-of-the-year indices remained relatively steady with low levels of adult harvest, the population did not show signs of recovery. A stock assessment conducted in 2009 examined other potential factors that could affect natural mortality in addition to predation, including seasonal variables such as water temperature and large-scale, environmental phenomena including the Atlantic Multidecadal Oscillation (NEFSC 2009). However, the 2009 assessment was unable to identify a driving factor affecting mortality, although competition and predation from striped bass and spiny dogfish were not ruled out. The most recent peer reviewed assessment conducted in 2016 utilized several methods to estimate time-varying mortality including the relationship between catch and the Atlantic Multidecadal Oscillation (ASMFC 2016). As with the 2009 assessment, the 2016 assessment supported the hypothesis that natural mortality has increased since 1996 but was unable to determine the underlying cause or causes.

6.6.2 Description of Indicator

The primary indicator of weakfish productivity in the Delaware River Estuary is the mean catch per nautical mile of weakfish in the adult groundfish research trawl survey, conducted using a 30-foot otter trawl net in Delaware Bay by the Delaware Division of Fish and Wildlife. This survey has been conducted since 1966 (1966-71, 1979-84 and 1990 – present) and is conducted monthly from March through December at nine fixed stations in Delaware Bay.

Weakfish relative abundance in the 30-foot trawl survey has generally followed a declining trend since 1996 (Fig 6.6.2) and total mortality estimates have correspondingly increased. Despite annually ranking among the top one or two (by number) fish species encountered in the trawl survey, weakfish abundance remains below the historical average for the survey. However, abundance did increase in 2015 following three consecutive years of declining abundance (Greco 2016). The age structure of weakfish remains truncated similar to the age structure found in the early 1990s with 88% of survey catch being less than age two.

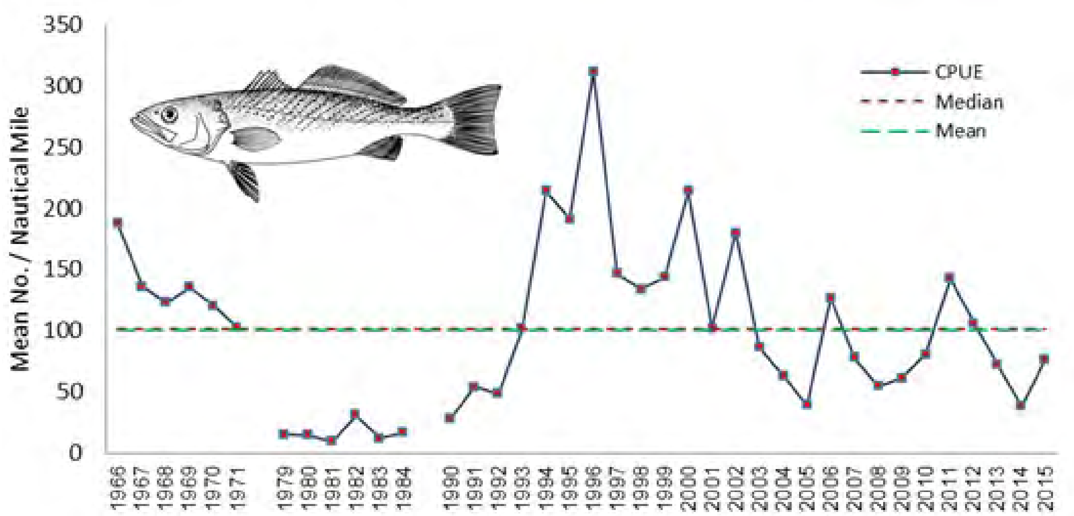

Figure 6.6.2 Weakfish relative abundance (mean number per nautical mile), time series (1966 – 2014) mean and median as measured in 30-foot trawl sampling in Delaware Bay.

A secondary indicator of weakfish productivity in the Delaware River Estuary is the index of relative abundance of young-of-the-year weakfish as measured by the Delaware Division of Fish and Wildlife's Juvenile Finfish Research Trawl Survey. This survey has been conducted annually since 1980 and samples monthly from April through October at 33 fixed stations in the Delaware Bay and River utilizing a 16-foot semi-balloon otter trawl. Abundance of young-of-year weakfish declined in 2015 relative to 2014 and dropped slightly below the time series mean (Fig 6.6.3) (Greco 2016).

Weakfish annually rank among the top species taken in the juvenile trawl. However, as with the relative abundance in the 30-foot trawl survey, the young-of-the-year index for weakfish has also followed a declining trend since 1996 (Fig 6.6.2). Recent recruitment levels have been above or near the historical average and, given the propensity of weakfish to reach sexual maturity by age 1, as studied by Nye et al. (2008), the above average recruitment could lead to an increase in the spawning stock biomass for the species, unless current very high levels of natural mortality continue.

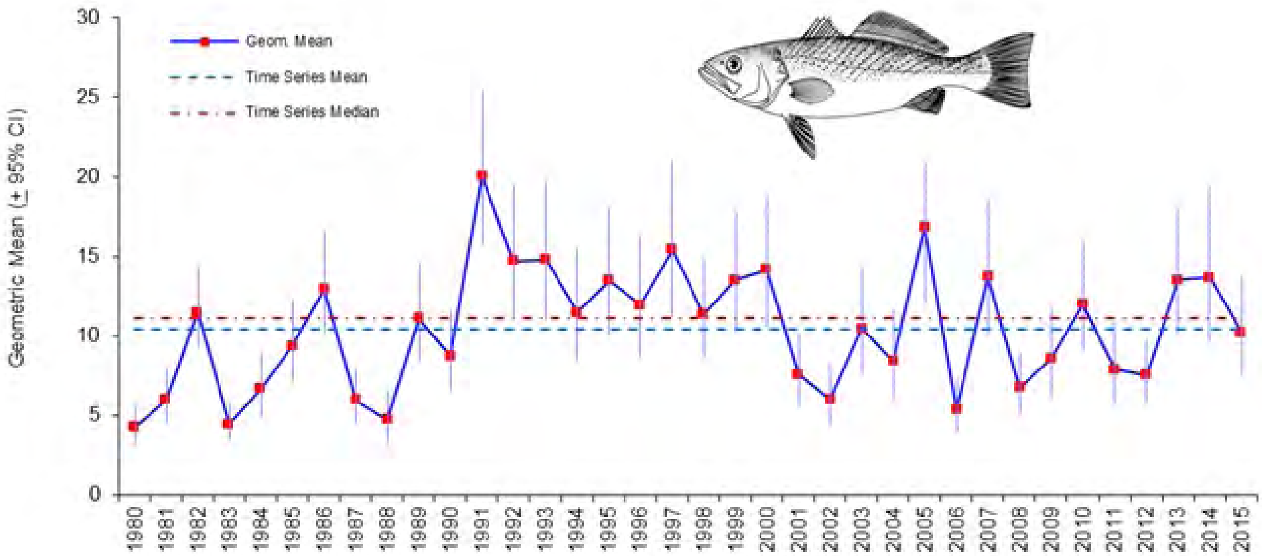

Figure 6.6.3 Relative abundance of young-of-year weakfish from 1980 through 2015, time series mean and median as measured by 16-foot trawl sampling in the Delaware Estuary.

6.6.3 Present Status

Despite a small increase in adult weakfish abundance in Delaware's adult trawl survey in 2015 and despite the fact that young-of-year recruitment in the estuary fluctuates around the historical average, the coastwide weakfish stock is considered depleted and has been for the past 13 years as detailed in the latest peer reviewed stock assessment (ASMFC 2016). Under the new reference points proposed in the latest assessment, the stock is considered depleted when the coastwide estimated spawning stock biomass is below 30% of the estimated average biomass over the period 1982-2014. The 2016 assessment estimated the spawning stock biomass to be 5.62 million pounds in the terminal year of the assessment (2014). Despite slight increases in total abundance and spawning stock biomass in recent years, the stock is well below the spawning stock biomass threshold and has been since 2003. Results of the latest assessment indicated that overfishing is not occurring, since total mortality (Z = 1.11) was below the current threshold (Z = 1.36). However, the assessment indicated that natural mortality has been increasing since the mid-1990s. As such, the weakfish population has been experiencing high levels of total mortality, which has prevented the stock from recovering (ASMFC 2016).

6.6.4 Past Trends

Weakfish were at moderate abundance prior to the 1970s, when they began an explosive rise in abundance and size. By the late 1970s, Delaware Bay had become famous throughout the Mid-Atlantic region as a destination for catching trophy-sized weakfish in the spring spawning run. By the late 1980s, this fishery declined somewhat; however, the Delaware commercial fishery landed over 200,000 pounds of weakfish as late as 2001. The Atlantic States Marine Fisheries Commission imposed significant fishery restrictions coastwide in the mid-1990s, and, in response, abundance and catches initially began to increase through the late 1990s, before declining during the 2000s. So, although the fishery has not regained the high catches and trophy sizes seen in the 1970-1980 period, it did produce higher catches of legal size weakfish for many in the mid- to late-1990s, before its ultimate decline. By 2007, Delaware commercial landings declined to 27,000 pounds. By 2010, no directed fishery was allowed on the Atlantic coast; only a small amount of bycatch was legal.

6.6.5 Future Predictions

The 2016 stock assessment indicated that in recent years, slight increases coastwide in total abundance, spawning stock biomass, and recruitment of age 1 fish have occurred. However, the stock remains well below the recommended threshold.

6.6.6 Actions and Needs

More investigation is warrented to examine causes of weakfish declines (ASMFC 2016), although some factors have been identified.

6.6.7 Summary

Currently, weakfish reproduction continues at moderate levels. Survivorship to catchable size, however, has declined greatly, to the point that catches of legal-size weakfish are uncommon in Delaware Bay. The cause of the decline has been linked to factors such as predation by striped bass and spiny dogfish, competition with striped bass for menhaden and, changes in environmental conditions (ASMFC 2006, NEFSC 2009). However, the most recent stock assessment (ASMFC 2016) claimed that explicit factors leading to the decline of weakfish require more investigation.

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Suggested Citation for this Chapter

Greco, M. 2017. "Chapter 6.6 - Weak Fish" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 247-250.

6.7 Horseshoe Crab

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6.7.1 Introduction

Horseshoe crabs (*Limulus polyphemus)* are benthic (or bottom-dwelling) arthropods that use both estuarine and continental shelf habitats (Fig 6.7.1). Although it is called a "crab," it is grouped in its own class (Merostomata), which is more closely related to the arachnids than blue crabs and other crustaceans. Horseshoe crabs range from the Yucatan Peninsula to northern Maine, with the largest population of spawning horseshoe crabs in the world found in the Delaware Bay.

Figure 6.7.1 Horseshoe Crabs spawning. Photo credit: Gregory Breese, U.S. Fish and Wildlife Service

Each spring, adult horseshoe crabs migrate from deep Bay waters and the Atlantic continental shelf to spawn on intertidal sandy beaches. Beaches within estuaries, such as the Delaware Bay, are believed to be preferred because they are low energy environments protected from wind and waves, thus reducing the risks of stranding during spawning events. Spawning generally occurs from March through July, with the peak spawning activity occurring on the evening new- and full-moon high tides in May and June.

Horseshoe crabs are characterized by high fecundity, high egg and larval mortality, and low adult mortality. Horseshoe crabs spawn multiple times per season, laying approximately 3,650 to 4,000 eggs in a cluster. Adult females lay an estimated 88,000 eggs annually. Egg development is dependent on temperature, moisture, and oxygen content of the nest environment. Eggs hatch between 14 and 30 days after fertilization.

Juvenile horseshoe crabs generally spend their first and second summer on the intertidal flats, usually near breeding beaches. As they mature, horseshoe crabs move into deeper water, eventually into areas up to a few miles offshore. Horseshoe crabs molt 16 to 17 times over 9 to 11 years to reach sexual maturity. Based on growth of epifaunal slipper shells (*Crepidula fornicata*) on their prosoma, horseshoe crabs live at least 17 to 19 years.

Larvae feed on a variety of small polychaetes and nematodes. Juvenile and adult horseshoe crabs feed mainly on molluscs including razor clam (*Ensis* species), macoma clam (*Macoma* species), surf clam *(Spisula solidissima*), blue mussel (*Mytilus edulis*), wedge clam (*Tellina* species), and fragile razor clam (*Siliqua costata*).

Shorebirds feed on horseshoe crab eggs in areas of high spawning densities such as the Delaware Bay. Horseshoe crab eggs are considered essential food for several shorebird species in the Delaware Bay, which is the second largest migratory staging area for shorebirds in North America. Shorebird predation on horseshoe crab eggs has little impact on the horseshoe crab population since horseshoe crabs place egg clusters at depths greater than 10 centimeters, which is deeper than most shorebirds can probe. Eggs utilized by shorebirds are brought to the surface by wave action and burrowing activity by spawning horseshoe crabs. The eggs brought to the surface not consumed by shorebirds or other predators desiccate in a short time in the sun, so do not contribute to productivity of the horseshoe crab population.

It is believed that adult and juvenile horseshoe crabs may make up a significant portion of the diet of the loggerhead sea turtle (*Caretta caretta*) in Delaware. Horseshoe crab eggs and larvae and adults are also a seasonally preferred food item of a variety of invertebrates and finfish, including sharks.

Historically, human activity appears to have resulted in reduced numbers of spawning crabs at two time periods. Between the 1850s and the 1920s, it is estimated that over one million horseshoe crabs were harvested annually for fertilizer and livestock feed. More recently horseshoe crabs have been taken in substantial numbers (e.g., over 5 million pounds in 1996) to provide bait for other fisheries, including (primarily) the American eel and conch fisheries. Since the early 2000s, harvest of horseshoe crabs for bait has been restricted multiple times and currently there is a moratorium on female harvest for bait in the Delaware Bay region.

Horseshoe crabs are also collected by the biomedical industry to produce Limulus Amebocyte Lysate (LAL). This industry bleeds individuals and releases the animals live after the bleeding procedure. LAL is used world-wide to test medical products such as flue serum, pace makers, artificial joints, and other items to help ensure public safety from bacterial contamination. No other known procedure has the same accuracy as the LAL test. If LAL became unavailable, it could take years to find a universally accepted replacement. Mortality associated with this use is estimated to be around 5-30%.

6.7.2 Description of Indicator

This indicator uses the Spawning Survey, which is conducted under the direction of the Atlantic States Marine Fisheries Commission's (ASMFC) Interstate Fishery Management Plan for Horseshoe Crab. The survey provides levels of spatial and temporal coverage that are effective for understanding trends in spawning activity at the bay-wide scale. Begun in 1999, this survey is published annually as a report to the ASMFC.

Beaches are sampled by volunteers using a stratified random approach. Sampling occurs 2 days prior, day of, and 2 days after the peak moon events (full and new moons) and at the highest of the daily high tides, which is the second or evening high tide. Protocol and data sheets and training are provided to volunteers. Each beach is sub-sampled using quadrats along transects that have random starts. Approximately 100 quadrats are sampled per beach. The quadrats are placed at the high-tide line and all horseshoe crabs that are at least halfway in the quadrat are counted and differentiated by sex (Figs 6.7.2 and 6.7.3).

The objective of the spawning survey was to estimate an index of spawning activity based on horseshoe crab density. It is important to recognize that this survey gives an estimate of density and should not be used to estimate population size. Instead it provides a useful measure of relative abundance or density of spawners and trends in spawning density.

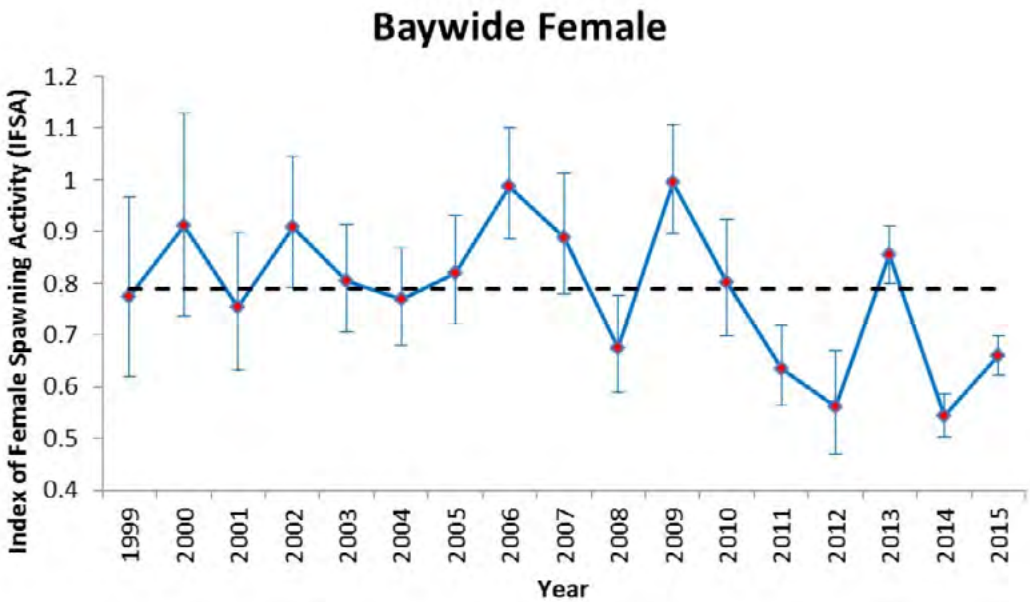

Figure 6.7.2 Index of female horseshoe crab spawning activity (IFSA) for the Delaware Bay from 1999 to 2015. Error bars are 90% confidence intervals. The dashed line is the mean value for the time series.

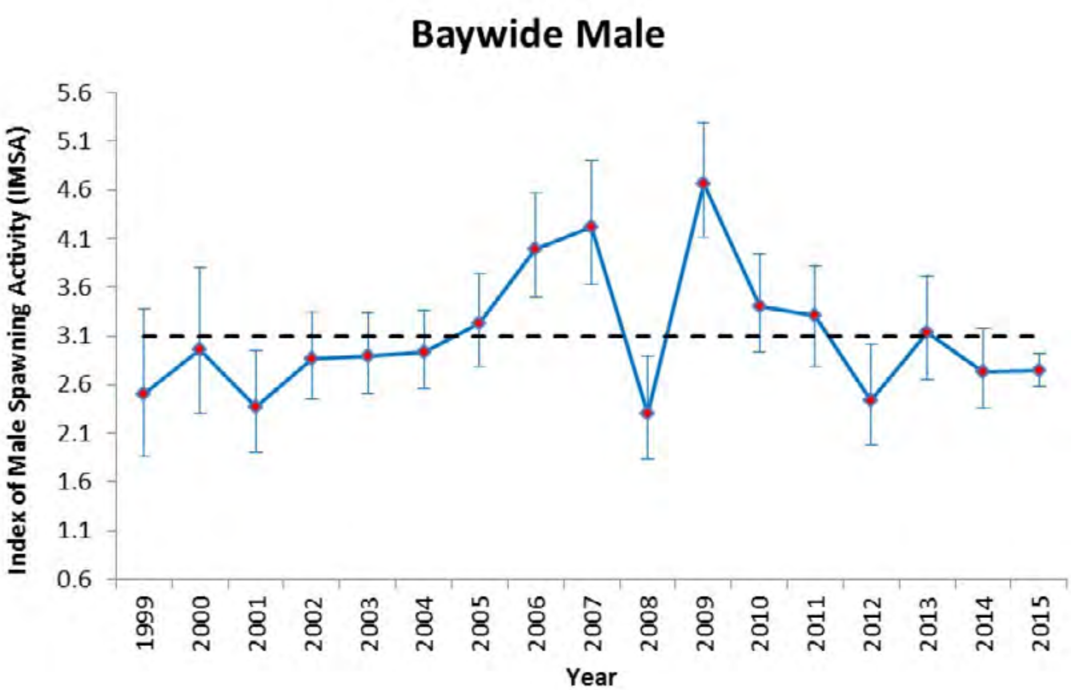

Figure 6.7.3 Index of male horseshoe crab spawning activity (IMSA) for the Delaware Bay from 1999 to 2015. Error bars are 90% confidence intervals.

6.7.3 Present Status

The latest report available is the 1999-2015 Spawning Survey Report, published May 25, 2016. In 2015 spawning peaked during the second lunar period sampled (May 16 – May 20). Spawning is well correlated with water temperatures.

6.7.4 Past Trends

Little data is available for measuring trends prior to 1990, but the population probably declined in the early 1900s due to overharvest and then increased through the 1970s. Bait overharvest led to another decline in the 1990s. The index of female spawning activity in both states exhibited a slightly negative slope, and the declining trend was statistically significant in Delaware. Baywide male spawning activity showed no significant trend from 1999 through 2015; though, the slope was positive.

6.7.5 Future Predictions

The ASMFC has implemented monitoring programs and restricted harvest of horseshoe crab with stated goals of maintaining a sustainable population for current and future generations of the fishing and non-fishing public, migrating shorebirds, and other dependent wildlife, including federally listed sea turtles. The National Marine Fisheries Service has established a horseshoe crab sanctuary off the mouth of Delaware Bay, the Carl N. Shuster Sanctuary. Watermen have voluntarily implemented the use of bait bags that reduce their need for bait by preventing bait from being consumed by non-target species. The Biomedical Industry has voluntarily implemented management practices to reduce stress to animals being held for bleeding. These measures can be expected to allow the spawning population to increase over time by reducing harvest and indirect mortality.

While there are indications the management actions to limit harvests, combined with voluntary reductions in bait use by watermen, will allow the population to increase, the current population trend for females does not yet show a positive trend and does not appear to be spawning at densities high enough to provide sufficient surface eggs to support historic levels of shorebirds during the spring stopover. Because horseshoe crabs are long-lived and do not reproduce until at they are 8-12 years old, it can take a decade or more for management actions to result in a measurable increase in the spawning population.

6.7.6 Actions and Needs

In order to better understand horseshoe crab population trends and their interaction with shorebirds, a cooperative effort between the ASMFC, States, US Geological Survey, and the US Fish & Wildlife Service has resulted in an Adaptive Management Framework for recommending harvest levels based upon population models that link red knot populations with horseshoe crab populations. Under this Framework, competing models that describe the dependence and interaction of red knots and shorebirds can be evaluated over time by monitoring the populations. Two monitoring programs are essential to implement this Framework: The Horseshoe Crab Trawl Survey and the Shorebird Monitoring Program at Delaware Bay. It will be critical to ensure funding for these two monitoring programs in order to increase our understanding and reduce our uncertainty regarding how these two populations interact.

6.7.7 Summary

Management of horseshoe crab harvest coupled with voluntary measures by the bait and biomedical industries can be expected to allow spawning populations of horseshoe crabs in Delaware Bay to increase over time. However, due to overharvest in the past, and the length of time needed (8-12 years) for horseshoe crabs to reach maturity, populations have not yet shown significant increases in terms of spawning densities relative to what were believed to be historical levels. Shorebirds dependent upon eggs that are exhumed by wave action and high densities of spawning horseshoe crabs are still at low levels and it is unclear whether current levels of surface eggs are high enough to support current levels of red knots and other shorebirds during typical weather conditions.

Since a portion of the red knot population that passes through Delaware Bay winters at the tip of South America and breeds in the high Arctic, other factors outside of Delaware Bay can, and probably are, affecting these populations. Work to help better understand the dependence of red knots on Delaware Bay is being carried out, in part, through a cooperative Adaptive Management Framework.

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Suggested Citation for this Chapter

Breese, G. 2017. "Chapter 6.7 - Horseshoe Crab" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 251-255.

6.8 American Shad

Desmond M. Kahn, PhD

Fishery Investigations

6.8.1 Introduction

American shad (*Alosa sapidissma*) is an anadromous species that is native to most major river basins on the Atlantic Coast of North America, including the Delaware River. It is a member of the family *Clupeidae*, or the herring family. The American shad has a lustrous green or greenish blue back with silvery sides and a white belly (Fig 6.8.1). Individuals may live up to 11 years and reach lengths over 20 inches. They are a popular, hard-fighting sport fish that can be taken on rod and reel using lures known as shad darts and flutter spoons, and they also have commercial value.

American shad are opportunistic feeders, whose freshwater diet includes copepods, crustacean zooplankton, cladocerans, aquatic insect larvae, and adult aquatic and terrestrial insects. After emigrating to offshore areas, American shad feed on the most readily available organisms, such as copepods, mysid shrimps, ostracods, amphipods, isopods, euphausids, larval barnacles, jellyfish, small fish, and fish eggs (ASMFC 2010). American shad spend most of their life at sea along the Atlantic coast and enter freshwater as adults in the spring to spawn. Stocks are river specific; that is, each major tributary along the Atlantic Coast appears to have a discrete spawning stock due to high fidelity to return to their natal tributary to spawn. In the fall or subsequent spring, juveniles emigrate from freshwater and estuarine nursery areas and join a mixed-stock, sub-adult coastal migratory population. Three primary offshore summer aggregations of American shad have been identified:
1) Bay of Fundy/Gulf of Maine, 2) St. Lawrence Estuary, and 3) off the coast of Newfound and Labrador.

Figure 6.8.1 Adult Shad caught in Schuylkill River, PA. Photo credit: Philadelphia Water Department.

After four to six years, individuals become sexually mature and migrate to their natal rivers during the spring spawning period. American shad that spawn north of Cape Hatteras are repeat spawners, while almost all American shad spawning south of Cape Hatteras die after one spawning season (ASMFC 2010). Repeat spawning has been documented for Delaware River shad via analysis of scales that reveal growth patterns, including patterns indicative of repeat spawning. In the Delaware, there can be as many as 5 year classes of adult shad participating in a spawning migration; however, the majority of spawning is represented by two age classes (Delaware River Basin Fish & Wildlife Management Cooperative 2016).

American shad have ecological, economic, cultural, and social significance (ASMFC 2010). Ecologically, they play an important role in freshwater, estuarine, and marine environments during their anadromous life cycle. They influence food chains by preying on some species and serving as prey for others throughout all life stages. Economically, American shad have supported valuable commercial fisheries along the entire Atlantic coast. In the late 1890s, the Delaware River had the largest annual commercial shad harvest of any river on the Atlantic Coast. The harvest began to decline rapidly in the early 1900s. Despite efforts in the late 1800s to increase the shad population through legislation and a massive program of artificial propagation, the shad fishery eventually collapsed. Sharp (2010) reports that a 1912 measurement indicates that the dissolved oxygen level was below the current legal requirement of 3.5 mg/L. Detectable water pollution in the River at Philadelphia was reported. By the 1940s, the commercial shad fisheries were mainly limited to the lower reaches of the River and Bay below Pennsylvania (ASMFC 2007). Culturally, American shad were and are of significance to Native Americans, European colonists, and contemporary Americans who reside near and/or fish in rivers that supported or continue to support spawning runs. Many communities celebrated and still celebrate the arrival of shad by holding festivals to mark the occasion. The most comprehensive account of the role that American shad has played in the culture of North America since colonization by Europeans is that written by John McPhee). Research from *The Founding Fish*, (McPhee 2002) documents the relevance of American shad in seventeenth and eighteenth-century America.

6.8.2 Description of Indicator

To investigate the status of this indicator, we used the following data:

- An annual relative abundance index in the upper, nontidal portion of the River, indicating the relative abundance of the annual spawning run. The index is the annual mean catch-per-haul rates from the Lewis Haul Seine operation at Lambertville, NJ. This fishery is a semi-commercial, government-supported, long term fishery operation that has recorded the number caught per seine haul since 1920. The Delaware River Fish and Wildlife Cooperative Committee subsidizes this haul seine because of its value as an index of the spawning runs. Very few fish are actually landed from this operation.

- Commercial harvest data from the Delaware Division of Fish & Wildlife and the New Jersey Division of Fish and Wildlife.

6.8.3 Present Status

The portion of the main stem Delaware River available as habitat extends up into the East and West Branches above Hancock, NY representing over 300 miles of unobstructed main stem access. However, all major tributaries to the main stem Delaware are dammed creating numerous blockages to historic spawning and rearing habitat. The two major tributaries, namely the Schuylkill and the Lehigh Rivers, do have existing fish passage facilities in place at many of their dams, but these are variable in their ability to facilitate upstream passage of American shad.

Tidal reach There is commercial fishery in the Delaware and New Jersey portions of the Estuary with mandatory reporting beginning in 1985 for Delaware and in 2000 for New Jersey. In New Jersey, as of 2016 there were 71 permits issued (31 commercial and 34 incidental) to allow catch of American shad. A total of 45 permitted fisherman reported landings during the 2016 season. A small minority of these permit holders actually land shad in any year; for example in 2010, only 14 fishers landed shad. American shad are also caught as bycatch in Delaware's commercial striped bass fishery that has a season beginning on March 1 and extending through April 31. Currently, commercial harvest levels are relatively low (Fig 6.8.2); in 2015 31,183 pounds were landed, while the peak landings in the last 10 years were in 2007, at 134,266. Since shad landed weigh on average about four pounds, these amount to 795 fish and 33,566 fish, respectively.

The trend of decreasing commercial harvests is not viewed as a reflection of decreasing stock size but rather the result of fewer commercial fisherman in addition to a shift toward the harvest of the more valuable striped bass which are present in the estuary during that American shad migrate through (R. Allen, New Jersey Division of Fish & Wildlife and D. Kahn Delaware Dept. of Fish & Game, personal communication).

Nontidal reach The Lewis Haul Seine fishery at Lambertville, New Jersey is several miles above Trenton. This fishery has provided the mean annual catch per seine haul for an amazing 91 years, which makes it one of the most extensive time series of relative abundance data in the world. Currently the abundance level of the spawning runs are moderate. As discussed below under past trends, factors regulating abundance of American shad in the Delaware include dissolved oxygen levels and a probable negative effect of striped bass via predation.

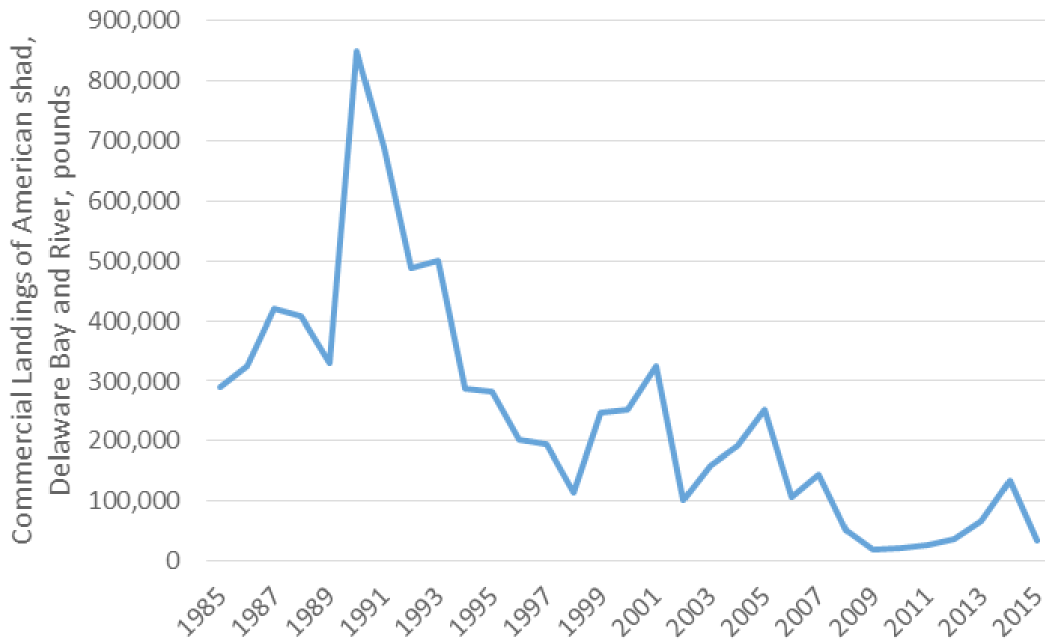

Figure 6.8.2 Commercial landings of American shad from the Delaware River and Bay. Delaware landings are from 1985 through 2015; New Jersey landings are only included from 2000 through 2015. Data supplied by the Delaware Division of Fish and Wildlife and the New Jersey Division of Fish and Wildlife.

6.8.4 Past Trends

The harvest began to decline rapidly in the early 1900s due to water pollution and dams on major tributaries. Despite improved state legislation and regulation, and a massive program of artificial propagation of shad stocks in the late 1800s, the shad fishery eventually collapsed under the combined pressures. By 1950, the urban reach of the Delaware River was one of the most polluted stretches of river in the world (ASMFC 2007). Pollution continued to be a major factor until passage of the Federal Clean Water Act in 1972. This Act was instrumental in the elimination of the "pollution block" of low or no dissolved oxygen in the region around Philadelphia. By 1973 the majority of spawning took place above the Delaware Water Gap more than 115 river miles upstream. American shad can now freely pass through this area during the spring spawning run as well as the fall out-migration.

In the late 1890s, the Delaware River had the largest annual commercial shad harvest of any river on the Atlantic Coast, with some estimates of up to 19 million pounds in a given year, although the accuracy of these estimates is questionable. As the Lewis Haul Seine data begins in 1925, abundance is low to moderate from 1925 through 1945. This was likely influenced by poor water quality, since very poor dissolved oxygen readings were detected as early as 1915 by the Philadelphia Water Department, below the current required 24-hour average level of 3.5 milligrams per liter. By 1948, abundance was near zero until a spike in the early 1960s, which returned to former low levels by 1966. However, as pollution controls were enacted under the federal Clean Water Act beginning in 1972, the runs increased by the late 1970s and through the early 1990s to very high levels, producing a booming recreational fishery in Pennsylvania and New Jersey. By the early 1990s, however, the runs began to decline, dropping to very low levels in the 2000s. Fishery managers responded by closing down a gill-net fishery along the ocean coastline in late winter and early spring by 2005; abundance did not increase, however.

A hypothesis developed from extensive studies on the Connecticut River is that declines during the 1990s and 2000s in abundance of American shad and river herring have been caused by the unprecedented increase in historical times of the abundance and size of striped bass and the predation they conduct (Savoy and Crecco 2004). That hypothesis held up to statistical testing and is supported by numerous publications showing that striped bass prey on alosids during spring in rivers, including consumption of adult shad. The Delaware River spawning stock of striped bass was declared restored by the Atlantic States Marine Fisheries Commission based on a report by Kahn et al (1998). Based on the corroboration of this predation hypothesis in the Connecticut River stocks, the hypothesis was tested for the Delaware River spawning stock as part of the stock assessment of the Delaware River stock by the Delaware River Cooperative Fish and Wildlife Management Technical Committee (DRBFWMC 2011). This test consisted of a correlation or regression analysis of the relative abundance of striped bass in the waters of the state of Delaware from the Marine Recreational Information Program and the mean catch-per-haul index of American shad relative abundance from the Lewis Haul Seine fishery. A negative correlation or regression (depending on the way this analysis is perceived) corroborates the hypothesis. This negative relationship is, in fact, highly significant (Fig 6.8.3), supporting the hypothesis that striped bass predation is a major cause of the decline in shad abundance from the peak levels in the 1980s and early 1990s.

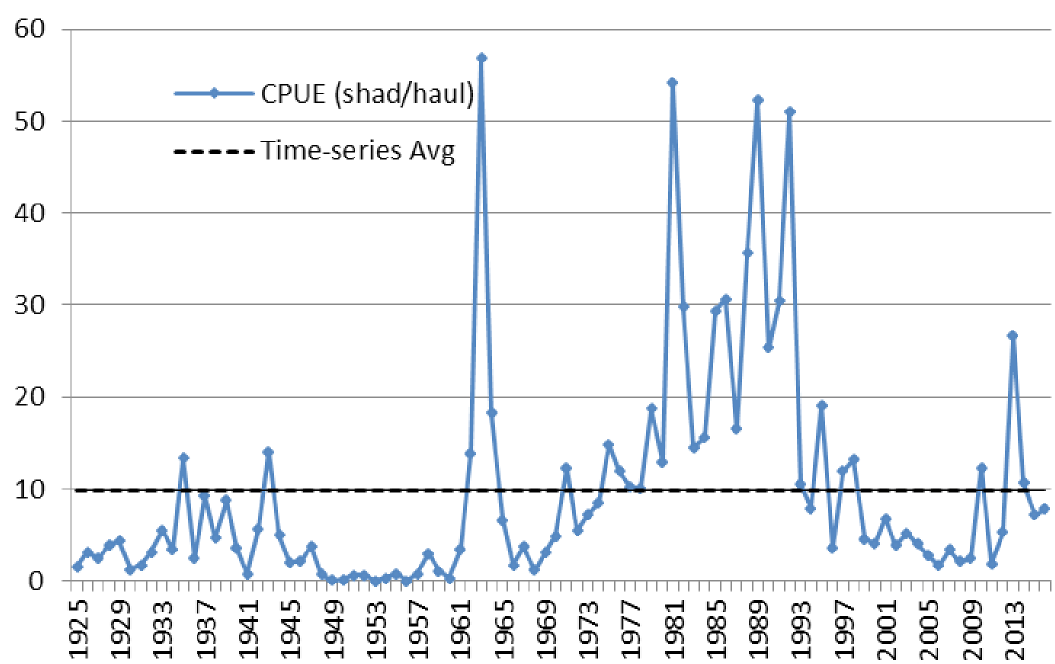

Figure 6.8.3 Mean annual catch per seine haul of American shad in the nontidal Delaware River at Lambertville, New Jersey in the Lewis Haul Seine fishery from 1925 through 2016. Data supplied by the Lewis Haul Seine operation.

6.8.5 Future Predictions

The current fishery for the Delaware River stock of American shad has been found sustainable under current recreational and commercial conditions (Delaware River Basin Fish & Wildlife Management Cooperative 2011, 2016). The current management plan for the Delaware River stock has precautionary benchmarks that could be used to trigger management actions designed to prevent stock collapse, established by the Delaware River Basin Fish and Wildlife Management Cooperative. An overall population increase could be realized with on-going attempts to improve fish passage on both the Schuylkill and Lehigh Rivers. Dam removal activities also on-going in the Brandywine and Musconetcong Rivers will also provide access to historic spawning areas for American shad, allowing a potential increase in the population. However, the predation hypothesis seems to predict that, if the current conservative management of striped bass by the Atlantic States Marine Fisheries Commission continues, the resulting predation pressure from the high number of very large striped bass will likely prevent a major increase in shad abundance in the Delaware.

6.8.6 Actions and Needs

Any improvement in restoring access to blocked habitat through dam removal or improvements in fish passage devices on existing dams would facilitate population increases for American shad in the Delaware River.

Currently, there is no vehicle funding specific for protection and enhancement of the Delaware River shad population. However, a recently passed federal law, the Delaware River Basin Conservation Act, could establish a federal program at the U.S. Fish and Wildlife Service to coordinate and prioritize restoration efforts for numerous species and habitats throughout the Delaware River watershed. Currently, however, this act lacks funding. Restoration activities that would benefit American shad should be considered for use of a portion of any funds supplied, particularly dam removal and fish passage.

6.8.7 Summary

In summary, the current condition of the American shad population in the Delaware River is healthy but moderate when compared to the boom period of the 1980s and 1990s. Although no data exists prior to 1925, reported landings from the late 1800s were enormous, and of questionable accuracy, although they suggest the Delaware River shad stock was far more abundant than it is today. In addition to environmental and social benefits, increases in the population of American shad would provide economic benefits through increased revenues for local communities from recreational angling and commercial fishing. The Delaware River stock of American shad has been twice found to be sustainable under current conditions, with the establishment of benchmarks established by the Delaware River Basin Fish and Wildlife Management Cooperative. These benchmarks are designed to react to declining trends in abundance. Statistical testing could not reject the hypothesis that striped bass predation is negatively correlated with American shad abundance in the Delaware: the potential mechanism is the documented predation on shad by striped bass. This evidence suggests that, if striped bass abundance remains high, American shad abundance in the Delaware will remain moderate to low.

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Suggested Citation for this Chapter

Breese, G. 2017. "Chapter 6.8 - American Shad" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 256-261.

6.8.9 Schuylkill River American Shad Stock Restoration

L. H. Butler and J. A. Perriilo • Philadelphia Water Department

The Schuylkill River, the largest tributary to the Delaware River, supported large numbers of American shad (*Alosa sapidissima*) until the construction of dams and lock systems in the early 1800's. Historical records indicate that shad and river herring (Alewife, *Alosa pseudoharengus* and Blueback Herring, *A. aestivalis*) ascended the Schuylkill River as far upstream as Pottsville (160 rkm), but have not done so since 1820, when Fairmount Dam was built (Mulfinger and Kaufmann 1981). For more than 150 years, American shad appeared to have been extirpated from the Schuylkill drainage (Sykes and Lehman 1957) until their presence in the tidal portion was revealed by Pennsylvania Fish and Boat Commission (PFBC) biologists in the 1970's. Since its inception in 1979 and subsequent rehabilitation in 2009, the Fairmount Dam Fishway has served as a focal point for scientists to ascertain the status of the shad spawning migration as well as the efficacy of fish passage through Fairmount Dam (Fig 6.8.9.1). Standardized community surveys conducted between April 1st and July 1st by the Philadelphia Water Department (PWD) below the dam enable researchers to measure relative abundance of *A. sapidissima* through a metric known as Catch-Per-Unit-Effort (CPUE). Similarly, time-lapse video monitoring during spring migration at the dam also provides vital information on the efficiency of the ladder to pass fish and the proportion of *A. sapidissima* that are successfully navigating through the fishway.

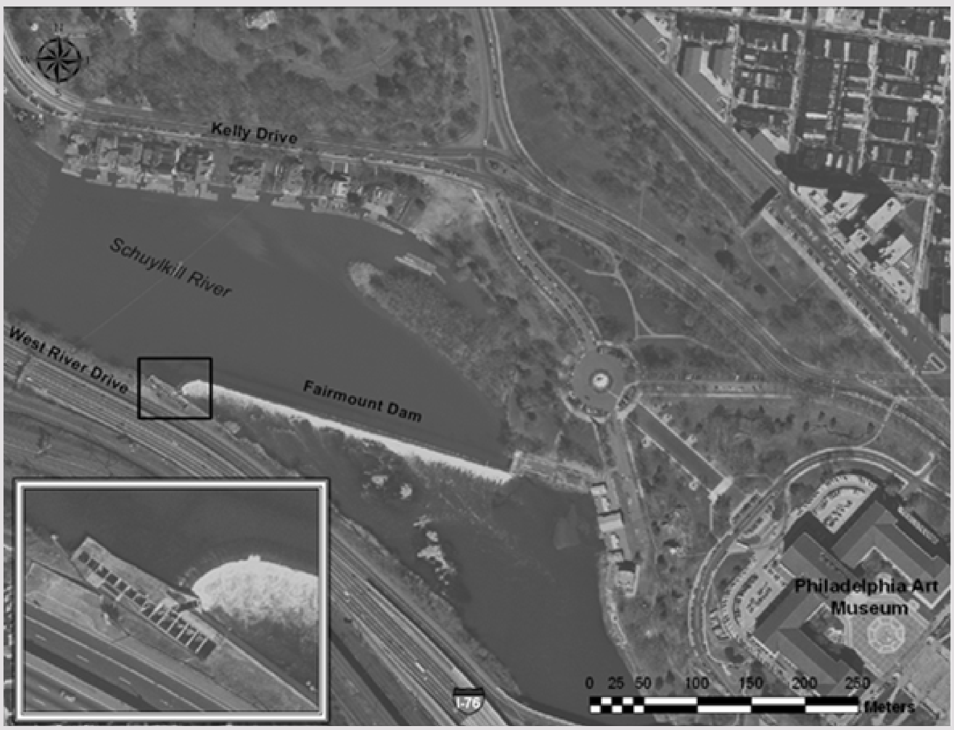

Figure 6.8.9.1 Aerial view of Fairmount Dam and vertical slot fishway (left insert) located on the west bank of the Schuylkill River at river km 13.6, Philadelphia, Pennsylvania. Courtesy: Perillo and Butler (2009).

Between 2004 and 2015, the relative abundance of American shad below the Fairmount Dam has shown high interannual variability, with the highest CPUE values occurring in 2010 and 2011 (13.43 and 15.80 fish/minute, respectively) (Fig 6.8.9.2). Prior to the restoration of the Fairmount Fishway in 2009, the highest number of shad passing through the dam was only 254; however, in 2011, 3,366 American shad successfully navigated through the Fairmount Fishway to upstream spawning grounds. In 2013 however, operational issues with the downstream regulating gate limited the efficiency of shad passage, and in 2014, severe flooding in the

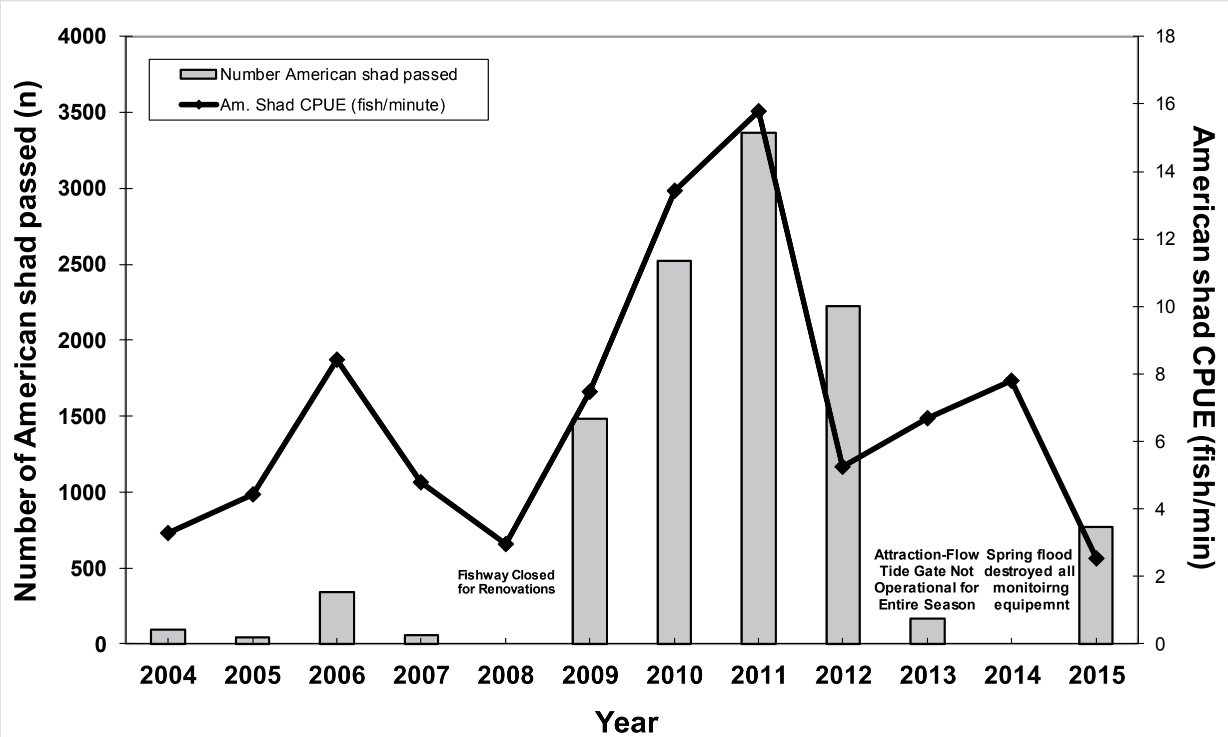

Figure 6.8.9.2 American Shad *(A. sapidissima)* passage and relative abundance at the Fairmount Dam (2004-2015). *Courtesy:* J.A. Perillo and L.H. Butler (Philadelphia Water Department).

fishway's monitoring room contributed to the loss of all video equipment and monitoring data.

Despite the low catch-per-unit-effort value of shad below the dam for 2015 and the low number of American shad passing through the fishway (n=771), it should be noted that the total number of all species of fish that passed through the fishway in 2015 (between April 1st-July 1st) was the highest in the 36-year history since the construction of the fishway in 1979. In total, 58,922 fishes representing 20 species successfully passed through the Fairmount Fishway. Of the 20 species documented ascending the fishway, 52,923 Gizzard Shad (*Dorosoma cepedianum*) were recorded. This suggests that the fishway can pass greater numbers of American shad provided they arrive in greater abundance below the dam.

To improve the density of American shad returning to the Schuylkill River, Philadelphia Water Department is developing a pilot program aimed at augmenting existing American shad stocking conducted by the Pennsylvania Fish and Boat Commission. Presently, PWD scientists have implemented a study at the Fairmount Fishway using live tank-spawning techniques. This 3-5 year study is intended to identify the relative success of alternative spawning techniques, bolster returning shad numbers to the Schuylkill River, and provide scientists with insight on the level of effort needed to implement a full-production facility.

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Suggested Citation

Butler, L. and J. Perrilo. 2017. "Chapter 6.8.9 - Schuylkill River American Shad Stock Restoration" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 262-264.

6.9 Eastern Oyster

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6.9.1 Introduction

Oysters are a dominant structural and functional member of the Delaware Bay benthos. The species native to Delaware Bay is *Crassostrea virginica* (Gmelin 1791), commonly called the eastern or American oyster (Fig 6.9.1). Eastern oysters are reef builders that provide hard substrate and create structural complexity in an environment otherwise dominated by sand and mud. This species occurs from Nova Scotia to Florida, throughout much of the Gulf of Mexico and south to Brazil. In some areas like South Carolina and Georgia, it can form extensive intertidal reefs but in Delaware Bay it is predominantly subtidal where it is protected from freezing and ice scour. In addition to providing habitat for many other species, oysters filter large quantities of water that enhance nutrient cycling within the system. Oysters have been harvested from Delaware Bay since pre-colonial times, and current harvests are carefully managed to support a sustainable fishery. Oysters have also been cultivated in Delaware Bay for more than a century in both intertidal and subtidal habitats of the lower Delaware Bay.

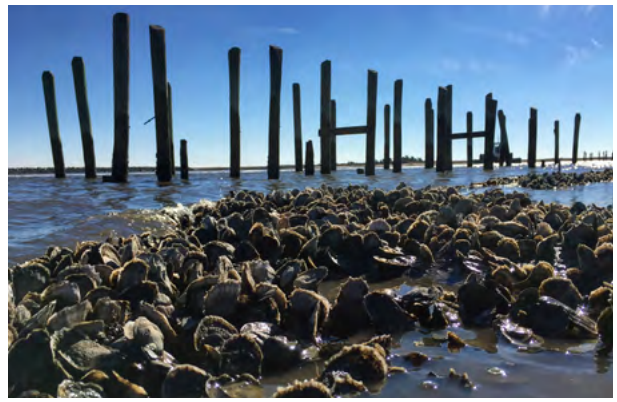

Figure 6.9.1 Oyster reef exposed at low tide in the Mispillion River, DE. Photo credit: Spencer Roberts, Partnership for the Delaware Estuary.

Oysters occur throughout Delaware Bay from Artificial Island to the mouth of the Bay and extend up into tributaries until salinity falls below tolerable average levels of about 5 ppt. Some oysters live intertidally, often on or within ribbed mussels along creek banks or attached to other hard substrates, natural or otherwise, within the lower intertidal zone. Nevertheless, the vast majority of the oyster population exists subtidally on reefs or beds that occur in the upper portion of the Bay above Egg Island Point on the New Jersey side and Port Mahon on the Delaware side upbay to Artificial Island. About 90% of the oysters in this region occur on the New Jersey side of the Bay.

Oysters may begin spawning in Delaware Bay as early as May or as late as September, but most spawns take place in July and August. Females can release all their eggs at once or partially spawn multiple times, but an average mature female may produce 2 to 60 million eggs during a single spawn. Typical spawns in a hatchery yield 1 to 15 million eggs. The fertilized eggs produce free swimming larvae within 24 hours that remain in the water column for two to three weeks before attaching to whatever hard substrate they can find, preferably clean oyster shell. During this process known as "setting" or "settlement", the settling larvae glues its left valve to the hard substrate then undergoes a metamorphosis, losing its ability to swim and taking on the morphology of a juvenile. Subsequent growth rate depends on the temperature, salinity, and food availability of the site where the oyster attaches and varies both seasonally and annually. By fall the young-of-year (YOY) oysters can range in size from a few millimeters to 40 or 50 mm with an average of around 25 mm. Little or no growth takes place during the winter, and young oysters are heavily preyed upon by oyster drills, flatworms, small crabs, and other predators. By the next fall most surviving oysters reach 30 to 65 mm depending on the location within the salinity gradient. Lower salinity areas have slower growth, but there are fewer predators so survival is better. Average growth to market size (3 inches = 76 mm) typically takes from 3 to 6 years in Delaware Bay, again depending on the location along the salinity gradient.

The oyster and the oyster reef assemblage are important to the general ecology of the Bay. The assemblage of organisms that develop on an oyster reef was recognized in the late 1800s as a community and described as a biocoenose by Möbius. This concept was the forerunner of what we now know as community ecology. In addition to the structure that oysters provide, they are also a major functional part of the ecosystem because oysters filter water for food. This filtration process removes particulate material from the water column and deposits it on the sediment surface where some of it becomes food for other organisms or is broken down by bacteria. This filtration and deposition is an important pathway for nutrient cycling in estuaries. In some estuaries, oyster filtration can clarify water enough to increase light penetration and facilitate growth of seagrasses but Delaware Bay is so turbid that this facilitation does not occur.

Two oyster diseases are present in Delaware Bay. MSX is caused by *Haplosporidium nelsoni*, and dermo or Perkinsosis is caused by *Perkinsus marinus*. Both pathogens are protozoans and neither affects humans, but they are eventually lethal to oysters. There is clear evidence that the native oyster population has developed a relatively high level of resistance to MSX (Ford and Bushek 2012), but resistance to dermo has not developed to any major extent (Bushek et al. 2012). Since 1989 dermo has been a major factor controlling oyster population levels on the higher salinity oyster beds in Delaware Bay from Ship John Light south.

6.9.2 Description of Indicator

The commercially harvestable oyster beds of the New Jersey portion of Delaware Bay have been surveyed in the fall and winter since 1953 (Fegley et al. 2003). In the earlier years, the survey took place from September throughout the winter, but since 1989 the period has been reduced to about one week in the last part of October to early November. A random stratified sampling method divides each of the beds into 0.2-min latitude x 0.2-minute longitude grids (~ 25 acres or 10,171 m_2) (Fig 6.9.2). Each bed is divided into three strata that are defined by surveys of the bed areas that are scheduled on a 10-year rotation. The bed area survey data are then divided into high quality, medium quality, and low quality. These represent high-density areas containing 50% of the population, medium-density areas containing 48% of the population, and low-density areas containing 2% of the oyster population. For the fall survey the grids in the high and medium quality categories are randomly sampled with the number of grids in each strata dependent on the variability of the particular bed as determined by the area survey and past sampling. Low quality grids are not sampled and the abundance of oysters on those grids, about 2% of the population, are never used in setting quota for annual harvest which averages less than 2% of the population contained within the high- and medium-quality areas. The annual fall survey is supplemented by regular monitoring of disease, mortality, and harvesting at weekly to monthly intervals. Details are published in annual stock assessment reports available at http://hsrl.rutgers.edu/SAWreports/index.htm

The oyster resources in the State of Delaware are about 10% of those in New Jersey because the habitable area on the Delaware side is smaller. The Delaware Division of Fish and Wildlife also conducts an annual survey of the Delaware oyster beds. It is less intensive than that of New Jersey, but it too relies on dredge samples and counts of live, dead, and newly set oysters to establish the upcoming annual harvest quota. For at least the past two decades, representatives from the Delaware Division of Fish and Wildlife have presented information from their survey at the stock assessment workshop.

6.9.3 Present Status

Population levels and harvest levels have been relatively steady at between 1 and 2 billion individuals and 70,000 to 100,000 bu (bu = 37 qts = 35 L), respectively, since 2002 in spite of a historically unprecedented period of low settlement that extended from 2000 through 2007 (Fig 6.9.3). The low recruitment coupled with the oyster disease dermo has reduced oyster stocks on the lower seed beds, but an active management program has sustained the overall levels of oyster abundance while permitting harvest. Subsequent increases in recruitment have stabilized the population.

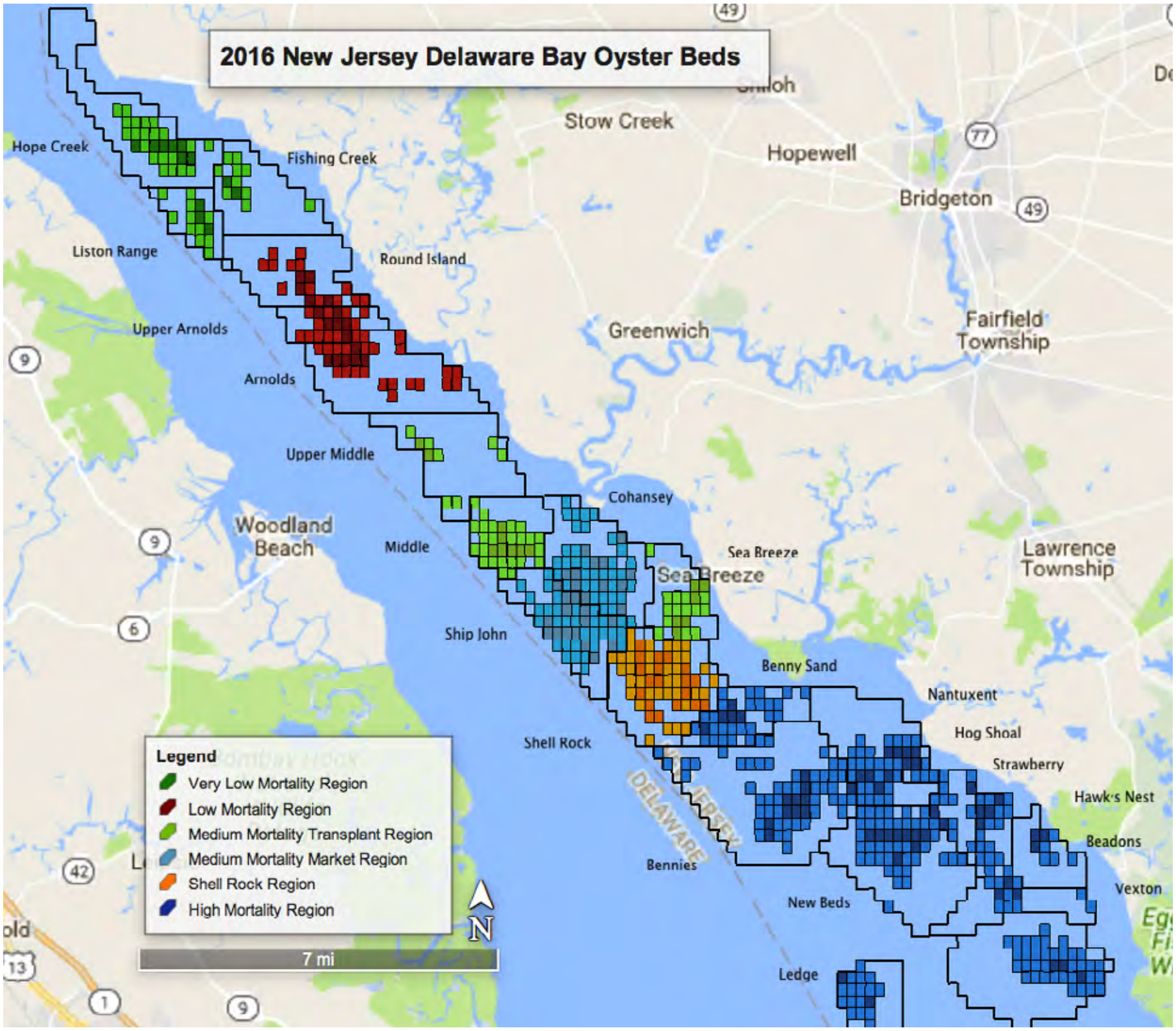

Figure 6.9.2 The assessed oyster beds of Delaware Bay, NJ grouped as regions (see Legend) with the 2016 strata designations. Black outlines indicate complete boundary of each bed with the high and medium quality strata grids in dark and light colors, respectively. The colors indicate region groupings although strata designations are within-bed not within-region. Clear blue areas in each bed indicate its low quality stratum. Annual assessments include samples from each bed's high and medium quality strata only. Each grid is 0.2" latitude x 0.2" longitude, approximately 25 acres (101,175 m^2 or 10.1 hectares). Courtesy of the Haskin Shellfish Research Laboratory, Rutgers University

Although Delaware has also developed quantitative estimates of absolute abundance, the Division of Fish and Wildlife relies primarily on estimation of trends in relative abundance. Population dynamic trends presented by Delaware at the annual stock assessment workshop tend to mirror trends on the New Jersey side.

6.9.4 Past Trends

There were substantial oyster harvests from Delaware Bay in the middle 1800's, and by the latter part of that century extensive importation of seed onto leased bottom in the lower Delaware Bay enhanced the numbers

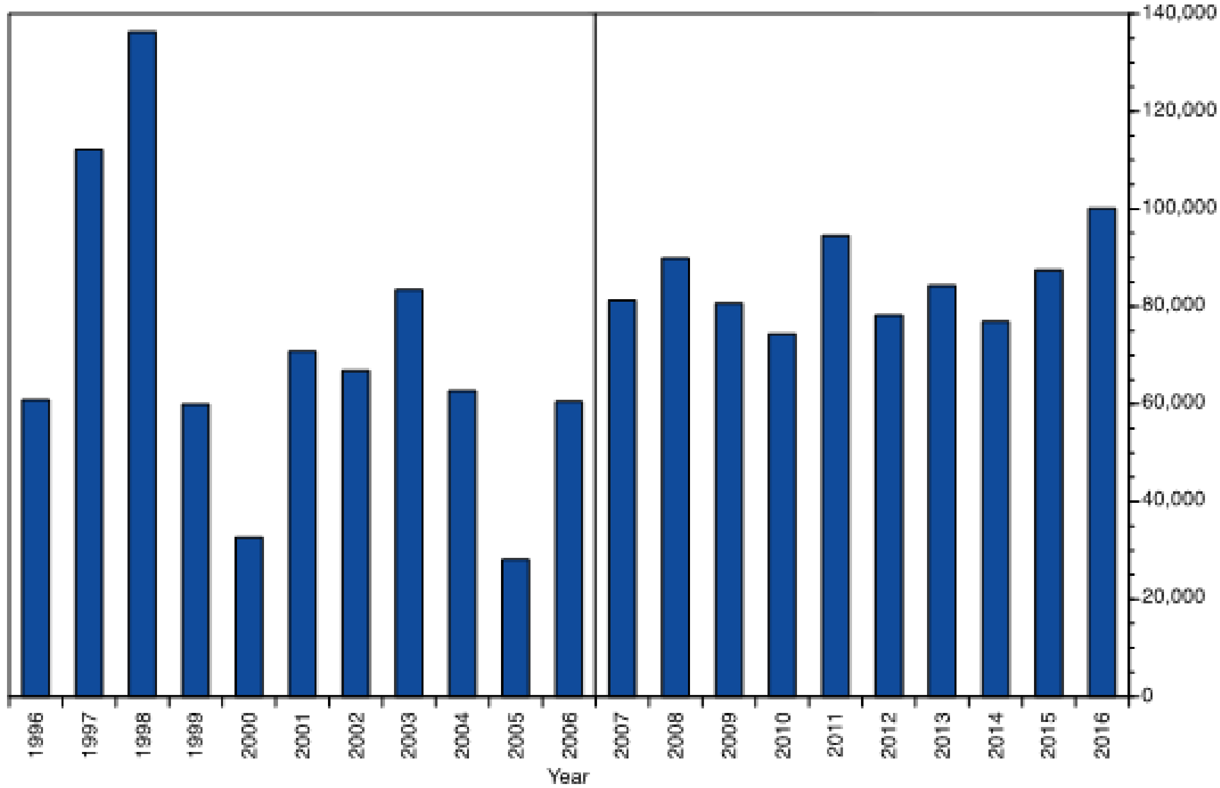

Figure 6.9.3 Oyster landings, in bushels, from the New Jersey Delaware Bay oyster beds from 1996 through 2016. Courtesy Haskin Shellfish Laboratory, Rutgers University.

of market oysters over what the Bay alone could produce. Active survey of the seed bed resource did not take place until 1953, and annual records are available since that date (Fig 6.9.4). The survey was initiated during a period of low abundance and just a few years before the oyster disease MSX substantially reduced the total numbers of oysters in the Bay. The following decade was a period of low abundance, but it was followed, from the late 1960's until the mid 1980's, by a period of high abundance. This was terminated by another MSX epizootic in 1985, and the emergence of dermo in 1989 which has dominated the population dynamics across the oyster beds ever since. In the late 1950's the natural oyster bed oyster population averaged about 2.8 billion adult individuals and it currently is about 1.75 billion individuals. In the peak years of the 1970's to the mid 1980's the average oyster population was tenfold higher at 17 billion individuals during a period when disease pressure was virtually non-existent.

6.9.5 Future Predictions

Management of this resource relies on annual survey data. Because the intensity of oyster diseases and recruitment success cannot be predicted, the only mechanism available for resource management decisions is the annual update of the oyster population information. There is no evidence that harvest has had substantial effects on the population dynamics of oysters in Delaware Bay since at least the late 1960's. Current recruitment levels indicate the stock is not recruitment limited, but may be substrate limited indicating that until the amount of habitat increases, likely via persistent large-scale shell planting, then the population will remain at this level. Presently, the oyster industry taxes itself at a rate that ensures it replaces what shell it harvests. Profit margins are such that increased taxes for shellplanting are not likely to be a viable mechanism for increasing shellplanting efforts which, ideally, would be on the order of half a million to a million bushels of shell a year. Current efforts are between 100,000 and 200,000 bushels.

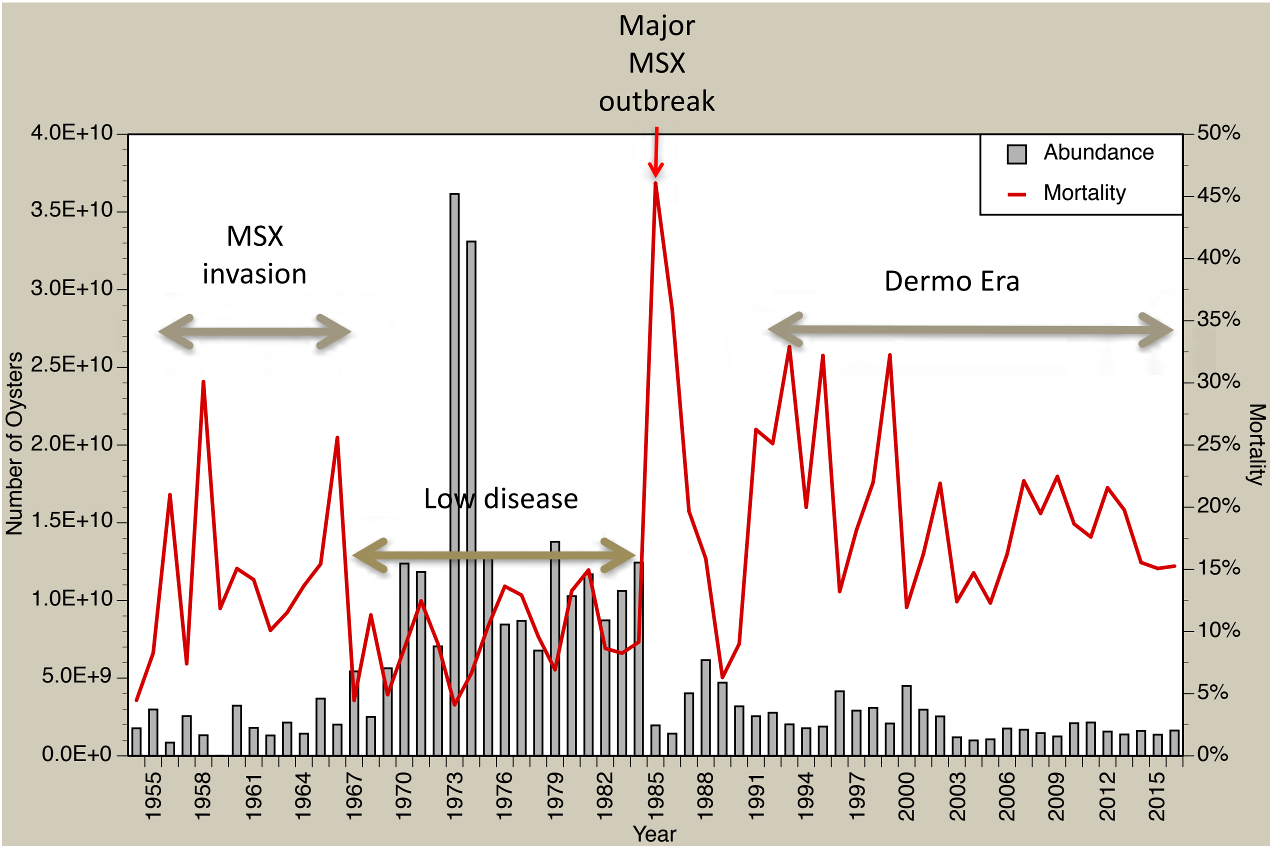

Figure 6.9.4 Annual estimates of oyster abundance on the New Jersey oyster beds in Delaware Bay from the Haskin Shellfish Laboratory annual dredge survey from 1954 through 2016, and annual total mortality estimates for the population.

Climate Change As long as the oyster population dynamics in higher salinity areas is controlled by dermo and MSX, changes in the oyster population will be linked to salinity levels. The funnel shape geomorphology of Delaware Bay makes the area available for development of oyster reefs less from the mouth of the Bay toward the fall line. Combining this geomorphology with ongoing sea-level rise suggest that the area available for prime oyster habitat will be reduced in the future. Other factors such as channel deepening, extraction of ground water, and consumptive use of Delaware River freshwater supplies all imply that salinity will rise even if climate change causes increased rainfall. Because freshwater in the Delaware River/ Bay system is actively managed, man made decisions may have more effects on the oyster population than modest climate change. If the most pessimistic climate change scenarios take place, there are likely to be such profound changes to the Delaware Bay system, and its human inhabitants that any change to the oyster resources will be of secondary or tertiary importance to the maintenance or movement of infrastructure. In 2011, however, excessive rainfall from Tropical Storms Lee and Irene depressed salinity throughout the Bay for several weeks causing up to 75% mortality on the uppermost beds (Munroe et al. 2013). It appears that those beds are recovering rapidly with higher than anticipated recruitment, but the flashiness of the system and its ability to produce freshets with similar impacts is expected to increase in frequency with climate change.

Oyster Aquaculture Oyster aquaculture is primed for growth in Delaware Bay with new developments in breeding for disease resistance and growth as well as technological advances in cultivation systems. Policies and regulations are being developed to guide this growth in a sustainable manner. Growth in intertidal aquaculture has already occurred, but has slowed due to potential concern about conflicts with federally listed threatened species. An adaptive management system has been employed to help work through these conflicts for the benefit of all. Meanwhile, advances in gear technology are being explored to facilitate growth of oyster aquaculture away from red knots, the threatened species that is currently raising concern.

6.9.6 Actions and Needs

The maintenance of the annual oyster population and oyster disease surveys is essential to management of this resource used to support the wild fishery. Efforts need to be made to evaluate the Hope Creek, Fishing Creek, and Liston Range oyster bed population dynamics. Plans need to be developed to manage the likely continued rise in salinity in Delaware Bay and its importance to the long-term viability of key oyster beds. At a minimum, development of a Bay wide monitoring system for temperature and salinity should be implemented. As possible additional parameters such as pH, dissolved and particulate nutrients, chlorophyll, and total suspended solids could be added. Plans for enhancing recruitment through shell planting need to be continued and expanded.

6.9.7 Summary

The oyster is a keystone species in the Delaware Estuary in that it provides a habitat, a harvestable resource, and a key link in ecosystem nutrient cycling. The oyster population abundance in Delaware Bay is currently controlled by a balance between recruitment and disease related mortality. Both of these processes respond to environmental factors such as the annual temperature cycle and salinity (freshwater input) and thus cannot be predicted. This unpredictability makes annual surveys a key to sustainably managing the resource. Recent good settlement of young indicates that the adult population will increase in the next few years. Shell planting to enhance recruitment is a mechanism for increasing population abundance, and should be continued and expanded.

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Suggested Citation for this Chapter

Bushek, D. 2017. “Chapter 6.9 - Eastern Oyster” in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 265-270.

6.10 Freshwater Mussels

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6.10.1 Description of Indicator

Freshwater mussels are filter feeding bivalve mollusks that live in lakes, rivers, and streams (Fig 6.10.1). Similar to oysters, freshwater mussels increase water clarity, enrich habitats, and furnish other important ecosystem functions such as stabilizing bed erosion (for summaries of ecosystem services, see: Kreeger and Kraeuter 2010; Anderson and Kreeger 2010).

The potential beneficial effects of healthy mussel beds on water quality are generating increasing research and restoration interest. Although vastly depleted in numbers and species richness compared to historical conditions, enough freshwater mussels appear to remain in the Delaware River Basin to materially contribute to water quality by their filtration. For example, Kreeger (2008) measured the abundance of *Elliptio complanata* in the Brandywine River and used survey data from Dr. W. Lellis (2001) (U.S.Geological Survey) to estimate that there are at least 4 billion adult mussels of this species across the Basin. Pairing these survey data with measured physiological processing rates, this species was estimated to filter about 10 billion liters of water per hour across the Basin, which is roughly 250 times the volume of freshwater entering the tidal estuary (Kreeger and Kraeuter 2010). More recently, a similar approach was used to estimate that representative beds of freshwater mussels in the tidal Delaware River upstream from Philadelphia filter more than a million gallons of water and 8 tons of suspended particles per day per hectare (Fig 6.10.2) (Kreeger et al. 2013).

Freshwater mussels grow more slowly than their marine counterparts. They also live longer (50 years or more) and have complicated reproduction strategies dependent on fish hosts. As long-lived, relatively sedentary creatures that process large amounts of water over their soft tissues, freshwater mussels are particularly sensitive to water quality and contaminants. The health, population abundance, and species diversity of freshwater mussels therefore represent excellent bioindicators of freshwater systems, particularly over long periods of time. Unfortunately, freshwater mussels are typically not sampled effectively as part of traditional macroinvertebrate assessments (Section 6.12), and so data on the status and trends of freshwater mussel populations are scarce.

6.10.2 Present Status

Freshwater mussels are the most imperiled of all animals and plants in North America (Nobles and Zhang 2011), which has the world's greatest diversity of this taxonomic group (> 300 species). More than 75% have special conservation status (Williams et al. 1993). At least 12 species are native to the Delaware River Basin (Ortmann 1919, PDE 2008, Campbell and White 2010); however, all but one species is currently reported to be uncommon (PDE 2008).

Figure 6.10.1 Freshwater mussels from the tidal Delaware River in May 2016. Photo credit: Danielle Kreeger, Partnership for the Delaware Estuary.

The leading causes of mussel decline in the Delaware River Basin are habitat and water quality degradation. Since freshwater mussels rely on fish, usually species-specific relationships, for successful reproduction dams that block fish passage can disrupt reproduction and gene flow (McMahon 1991, Neves 1993).

To assess present status, survey data were analyzed for the past 20 years from the portions of Delaware, New Jersey, and Pennsylvania that comprise the Delaware River Basin. Data were not available from the State of New Jersey (except limited recent Partnership for the Delaware Estuary surveys), and survey data were lacking for many areas of Delaware and Pennsylvania. Our analysis suggests that the overall condition of freshwater mussel populations is poor in streams where dams and other factors have progressively eliminated or reduced mussel populations over the past 100 or more years (Thomas et al. 2011).

Joint surveys in southeastern Pennsylvania by the Partnership for the Delaware Estuary (PDE) and the Academy of Natural Sciences of Drexel University between 2000 and 2010 found that only 4 of >70 stream reaches contained any freshwater mussels (Thomas et al. 2011). Even the most common native species are presently patchy in distribution and limited in abundance. Furthermore, most mussel populations that have been found appear to lack juveniles and be comprised mainly of older individuals, suggesting that many populations in Piedmont streams are not successfully reproducing. In contrast, recent surveys for freshwater mussels in Coastal Plain streams of southern Delaware and New Jersey suggest mussel populations are not as degraded (Cheng and Kreeger 2015). Similarly, extensive surveys of the undammed and tidal reaches of the mainstem Delaware River have revealed sometimes large beds of mussels (5-100 per square meter) (Lellis 2001, 2002, Kreeger et al. 2011). Several species found in the tidal Delaware River in 2010-1011 were previously believed to have been extirpated from the basin because they had not been reported in the published literature since Ortmann's surveys 100 years earlier (Ortmann 1919). Importantly, recent quantitative surveys of the Delaware River between Philadelphia, PA, and Trenton, NJ, revealed several locations with large numbers of juvenile mussels and up to 6 mussel species (Kreeger et al. 2013, 2015).

The condition of mussels on Coastal Plain streams and the tidal Delaware River is also healthier, as evidenced by lower shell erosion, richer tissue biochemistry, and a diverse population size range, compared to mussel populations in Piedmont streams, especially those with dams and stormwater impairments (Kreeger and Padeletti 2011, Gray and Kreeger 2014, Cheng and Kreeger 2015).

Figure 6.10.2 Freshwater mussels are filter-feeding bivalves that efficiently remove microparticulate matter, resulting in improved water clarity, greater light penetration, and beneficial transformation of many filtered pollutants. In this outreach demonstration from May 2015, both tanks received the same water, but the addition of 15 live mussels to the tank on the right had dramatically enhanced water quality within 4 hours. Photo credit: Danielle Kreeger, Partnership for the Delaware Estuary.

6.10.3 Past Trends

The most comprehensive historical regional mussel survey was conducted in Pennsylvania between 1909 and 1919 (Ortmann 1919). However, even by that time, dams and water quality degradation may have already affected mussel communities. Nevertheless, the study provided an excellent benchmark for gauging long-term trends in the mussel assemblage for the past 100 years.

Ortmann (1919) reported about 12 species of native mussels from the Delaware River Basin, most of which were present at that time in southeastern Pennsylvania (Fig 6.10.3). Although species richness was highest in the mainstem Delaware River even then, at least five species were present in several tributary watersheds, including the Schuylkill and Brandywine.

In contrast, figure 6.10.3 depicts the current species richness of native mussels (Thomas et al. 2011) for those sub-watersheds where surveys have been completed since 1996. Although the richness appears to have been preserved in the mainstem Delaware River and a few tidal tributaries in New Jersey, only one or no species has been detected in recent years in most surveyed tributary streams of Delaware and Pennsylvania (Fig 6.10.3).

A comparison in figure 6.10.3 also suggests that the range of native mussel occurrence has shrunk significantly during the last 100 years in streams where historic and recent survey data exist. This decline appears to be continuing. For example, no mussels have been found since 2002 in the upper White Clay Creek, Pennsylvania, despite annual surveys by PDE; whereas, two species were found there as recently as 1998-2001 (Fig 6.10.3).

6.10.3 Future Predictions

Since the decline of native mussel biodiversity has been attributed to habitat and water quality degradation, the future prospects for freshwater mussels are likely to hinge on careful watershed management. Human population is expected to grow by 80% this century in the basin, which threatens to exacerbate the stressors that have been affecting mussels for probably hundreds of years.

Climate change also threatens freshwater mussels (Kreeger et al. 2011) because of increased thermal stress and stormwater. Freshwater mussels are especially sensitive to bed instability and inputs of fine sediments to the system, and so stormwater and flood scouring represent threats that are expected to increase with climate change (Kreeger et al. 2010). Salinity rise also threatens mussels living in freshwater tidal areas. Since freshwater mussels depend on fish hosts for larval dispersal, it is unlikely that southern mussel species will be able to expand northward to fill niches that open if northern species are extirpated. The northern pearlshell, *Margaratifera margaratifera*, is an example of a cold-adapted species that uses brook trout as a host – its present distribution in southeast Pennsylvania is constrained to a few cold headwater streams and below reservoirs in the upper Schuylkill Basin which release colder water from the bottom. Assisted migration of warm-adapted southern species represents a potential climate adaptation tactic, but the willful introduction of species that are not native to this region might carry unforeseen risks and is at odds with current management paradigms.

Enhanced conservation and restoration efforts have the potential to offset projected continued declines in freshwater mussels (Kreeger and Padeletti 2011). Given the severely weakened status of freshwater mussel richness, range, and abundance, it is vital that any extant populations be protected. Although some streams may no longer be as suitable for mussels as they were historically, results from pilot reintroduction trials during 2007-2017 at more than a dozen locations in Delaware and Pennsylvania (Gray and Kreeger 2014, Kreeger et al 2014, 2015, Cheng and Kreeger 2017) suggest the majority of historic streams and ponds are still capable of sustaining mussels, but natural recolonization is prevented because of inhibited movements of suitable fish hosts. Mussel restoration in these areas can be accomplished by improving fish passage or

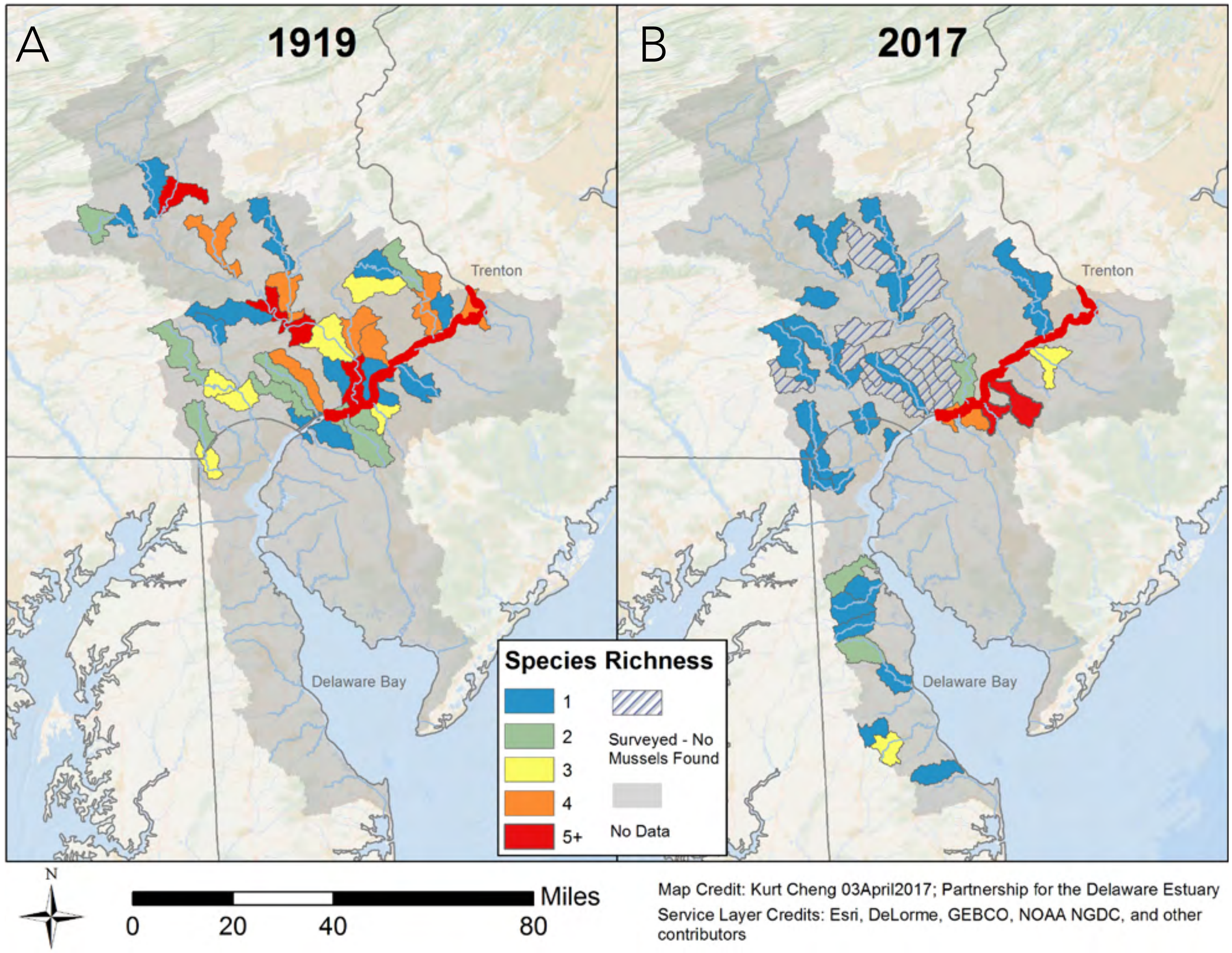

Figure 6.10.3 A) Species richness of native freshwater mussels reported in surveys conducted between 1919-1996, based on available data obtained by PDE. Surveys were primarily conducted by W. Ortmann prior to 1920 and A. Bogan during the 1980's. B) Species richness of native freshwater mussels reported in surveys conducted between 1996-2016. Surveys were primarily conducted by PDE with assistance in some areas by the Academy of Natural Sciences of Drexel University, Philadelphia Water Department, and Environmental Protection Agency Region 3 dive unit.

stocking of hatchery-propagated mussel seed. New restoration approaches such as building mussel beds within urban living shoreline projects have the potential to also boost mussel carrying capacity via habitat enhancement. Growing interest in mussel-mediated ecosystem services, such as water quality benefits, could energize mussel restoration in the Delaware River Basin.

6.10.4 Actions and Needs

More proactive freshwater mussel monitoring for species presence and population health is needed across the Delaware Estuary and River Basin. Freshwater mussels are not targeted in routine macroinvertebrate assessments, and so mussel surveys are rarely performed despite their value for assessing long-term status and trends of aquatic health. Hence, survey data are not available for most sub-watersheds of the Basin for at least 20 years, if ever. Improved coordination and data sharing among states and PDE would also facilitate development of better indicators and a coordinated watershed restoration strategy.

New survey technologies for mapping mussel beds and suitable habitats are being developed and should be marshalled to fill vital data gaps, identify mussel conservation areas, and help prioritize restoration areas. Critical habitat for mussel beds should be mapped and protected. The confirmation of freshwater mussel propagation and rare species in the tidal freshwater zone of the Delaware River is important because these represent potential source populations and broodstock to support the restoration of genetically appropriate mussels in other areas of the Basin.

We now have the technology to propagate juvenile mussels in a hatchery and rear them quickly in ponds for use in restoration projects. Monitoring of restoration outcomes is aided by electronic tagging methods, and biochemical and physiological fitness measures (e.g., Kreeger and Padeletti 2011, Gray and Kreeger 2014, Cheng and Kreeger 2014). More research is also needed on the habitat suitability traits that underpin mussel carrying capacity, which would directly benefit restoration practitioners interested in stream bed remediation or living shoreline projects.

Finally, additional research is needed to improve current models of the ecosystem service benefits of mussel conservation and restoration. Recent estimates suggest that the healthiest natural mussel beds in the tidal Delaware River may filter more than 1,000 pounds of nitrogen per hectare per year, but this number might be enhanced to >3,300 pounds per hectare per year in a designed nutrient bioextraction project (Kreeger et al. 2017). However, more research is needed to study the fate of the filtered matter and to predict whether mussel beds yield enough net nutrient removal to justify investments by water quality managers.

6.10.5 Summary

A robust community of freshwater mussels should be spread throughout the freshwater ecosystem and include diverse species that fill different ecological niches. Unfortunately, the present status of the dozen native species of freshwater mussels is poor in most areas of the Delaware River Basin, especially in Piedmont streams and areas with impediments to fish passage. Poor status was judged by the reduced biodiversity, abundance, and range for this taxonomic group. Continued watershed development and climate change represent increasing threats. Careful watershed management combined with more vigorous mussel conservation and restoration would help to offset these past and future threats to freshwater mussels. The few areas that still harbor healthy, diverse, and reproductive mussel beds, such as a few areas of the mainstem Delaware River, merit careful protection. Many areas that have lost mussel beds can now be restored using new technologies. Growing research is strengthening our understanding of the water quality benefits of healthy mussel assemblages and the economic basis for an increased restoration investment. The greatest improvements for water and habitat quality will likely be achieved by a basin-wide shellfish strategy that conserves and restores native bivalves living in different niches throughout the river-to-sea continuum.

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Suggested Citation for this Chapter

Kreeger, D. and K. Cheng. 2017. "Chapter 6.10 - Freshwater Mussels" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 271-277.

6.11 American Eel

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6.11.1 Introduction

American eels (*Anguilla rostrata*) are very unique among fishes of the Delaware River Estuary. Being catadromous, eels spend most of their lives in fresh and estuarine water, only returning to the open ocean to spawn (Fig 6.11.1). It is believed that all American eels spawn in the Sargasso Sea off the southern coast of the United States (Miller et al. 2014). American eels are also semelparous, meaning they spawn once and die. Larval stage eels (leptocephali) hatch from buoyant eggs, are leaf-like in shape, and drift on ocean currents westward to the eastern Gulf of Mexico and Atlantic coast of the U.S. All American eels are currently believed to spawn in one aggregation, and therefore offspring, with few exceptions, are genetically indistinguishable (Cote et al. 2013). Larval eels are not believed to return to the particular waters from which their parents came, but rather to migrate up the coast with the Gulf Stream and to move inshore in a randomized fashion. Recent findings suggest that ingressing juvenile eels are capable of conspecific cueing, using olfaction to select waters that are already occupied by other eels (Schmucker et al. 2016).

As leptocephali reach the continental shelf, they metamorphose into clear, very small eels known as glass eels and begin their inland migrations in late winter and early spring. Some eels will move far up into nontidal portions of Delaware River tributaries, often very small streams. Others remain in brackish water in tidal tributaries of the Bay and River. Once glass eels reach freshwater, they undergo pigmentation, eventually reaching the "yellow" phase of their life history, named as such for their yellow-green coloration. American eels spend most of their life in the "yellow" stage, residing in tributaries and the Delaware River for up to 30 years (Able and Fahay 1998) until they reach sexual maturity and the last stage of their life cycle, the "silver" phase. A number of physiological changes occur during the silvering process: the skin thickens, the body fattens, the shape and color of the pectoral fins change, the digestive tract degenerates, and the eyes become enlarged. These changes are thought to be beneficial for migration through the open ocean back to the Sargasso Sea (Facey and Van den Avyle 1987).

Figure 6.11.1 American eel caught in the Schuylkill Basin, Pennsylvania. Photo credit: Philadelphia Water Department.

Delaware and New Jersey have significant commercial fisheries for yellow eels in the Bay and it's tidal tributaries. Delaware landings have historically ranged above 100,000 pounds until 2008 when shortages in bait supply, namely female horseshoe crab, suppressed more recent annual landings (Fig 6.11.2). Eels are used by recreational fishers for bait to catch striped bass and large pelagic fishes such as tunas and billfish. A fairly robust bait market exists in the southeastern United States as well for cobia, catfish, and land-locked striped bass. Size of bait eels varies dependent upon the quarry targeted, but all must meet the legal minimum size of nine inches. The second market for eels is a food market both in this country and in Europe, where they are regarded as a delicacy. Eels are shipped live or frozen to Europe.

Delaware's eel fishery is reliant on a source of good bait; fishers say that, much of the year, the only bait that will catch significant numbers of eels is female horseshoe crabs. With the restrictions on horseshoe crab harvest along the Atlantic coast, availability has dwindled and the price of bait has increased to about $3 per crab in some areas. The price of bait has negatively impacted Delaware's eel landings in two ways. First, the catchability of other bait types including fish wracks and blue crabs is not as great as it is for horseshoe crabs. Secondly, many eel fishermen accustomed to catch rates of pots employing horseshoe crab baits have left the fishery presumably due to a decline in profitability. As a result, a sharp decline in commercial landings have been observed since regulations were enacted (2007) banning the harvest of female horseshoe crabs in the Delaware Bay region (Fig 6.11.2).

The American eel population is managed under regulations developed by the Atlantic States Marine Fisheries Commission. Coast-wide populations have declined in recent years, thought to be due to several potential factors, including the relatively slow rate of maturation, high levels of stage specific mortality, fishing mortality on a wide range of year classes prior to spawning, continued habitat loss in the form of dams and other impediments to upstream migration, and changes in oceanic conditions. Additionally, the introduced Asian parasite, *Anguillicola crassus,* is now wide-spread in the American eel population, as it has been documented in every State on the Atlantic coast. Relatively little is known about the overall effects this parasite has on the population, but the fact that it weakens, and in some cases, totally destroys the eel's swim bladder intuitively equates to a negative impact on infected eels. The United States Fish & Wildlife Service (USFWS) conducted a review of the species status in order to determine whether it should be listed under the Endangered Species Act (ESA). The USFWS had previously concluded in 2007 that there was no basis for listing eels as threatened or endangered. After reviewing the data again in 2015, the USFWS decided that listing the American eel under the ESA was again not warranted (USFWS 2015).

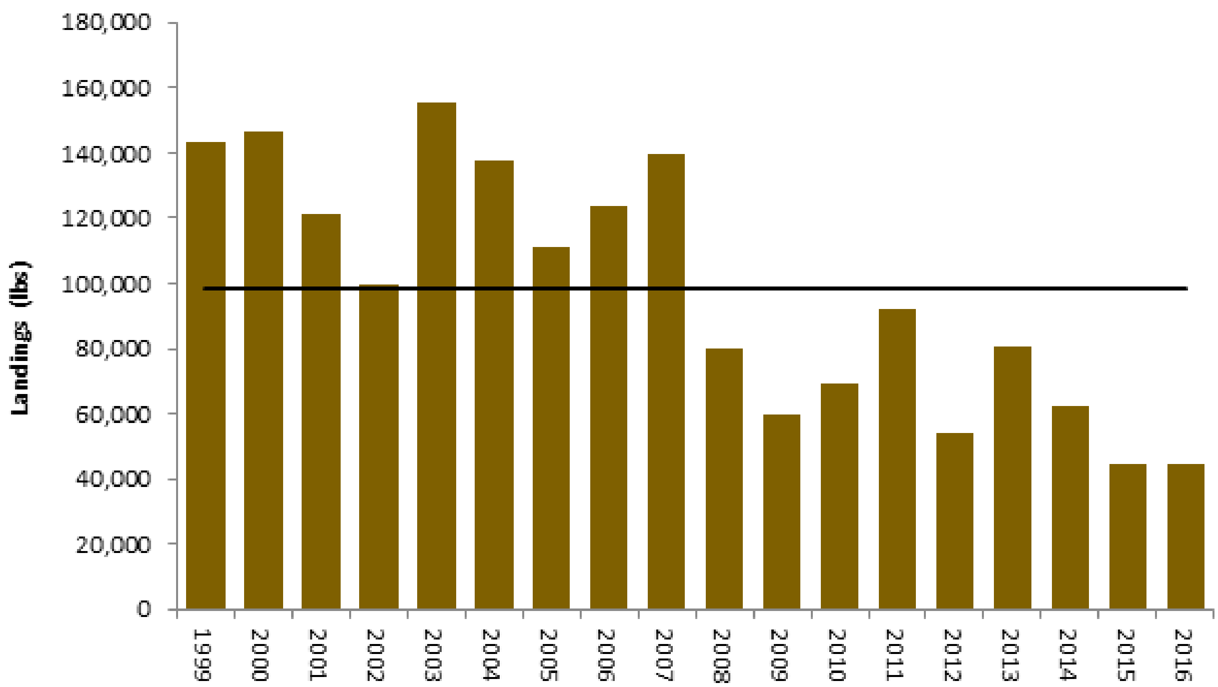

Figure 6.11.2 Delaware American Eel landings for the years 1999 – 2016. The black line represents mean landings for the time series.

6.11.2 Description of Indicator

The index of eel relative abundance is developed from 13 trawl survey stations in the lower Delaware River by the DE DFW Juvenile Finfish Trawl Survey. The net is a 16-ft (4.8-m) semi-balloon trawl with a 0.5-in (1.3-cm) cod end liner towed by 62-ft (19-m) R/V First State. The geometric mean catch-per-tow, using catch data collected from April through June, is used to estimate an index of abundance (Fig 6.11.3). Catch typically consists of eels from ages 0 to 7, with 3 years of age representing the most frequent age observed in the catch (DE DFW Unpublished data). All eels captured in this survey are yellow-phase.

A linear regression line was found to best represent the index as a function of year, which explains a statistically significant portion of the annual variability ($P = 0.01$, $R^2 = 18.3$). Such patterns raise the possibility of decadal-scale oscillations in climate affecting recruitment into the stock. Changes in cyclical climatic events have been found to affect patterns of abundance through cumulative effects on ecosystem processes including, but not limited to spawning success, primary productivity, and larval transport (Nye et al. 2014).

6.11.3 Present Status

Eel abundance in the Estuary as represented by the index, has increased in recent years with the last two years exhibiting the highest abundance estimates of the time series (Fig 6.11.3). All indications from anecdotal accounts from fishermen and biologists are that eel abundance is currently very high. Glass eel abundance surveys in Delaware and New Jersey have documented above average recruitment over the past four years. Although these surveys do not occur within the Delaware River watershed, they generally speak to recruitment trends in the region.

6.11.4 Past Trends

Abundance declined somewhat during the 1980s, but increased to higher levels in the mid-2000s. Sykes and Lehman (1957) reported that eel weirs were so numerous on the nontidal Delaware River that they trapped and killed many, if not most, young-of-year shad migrating downriver in early fall. These weirs targeted the

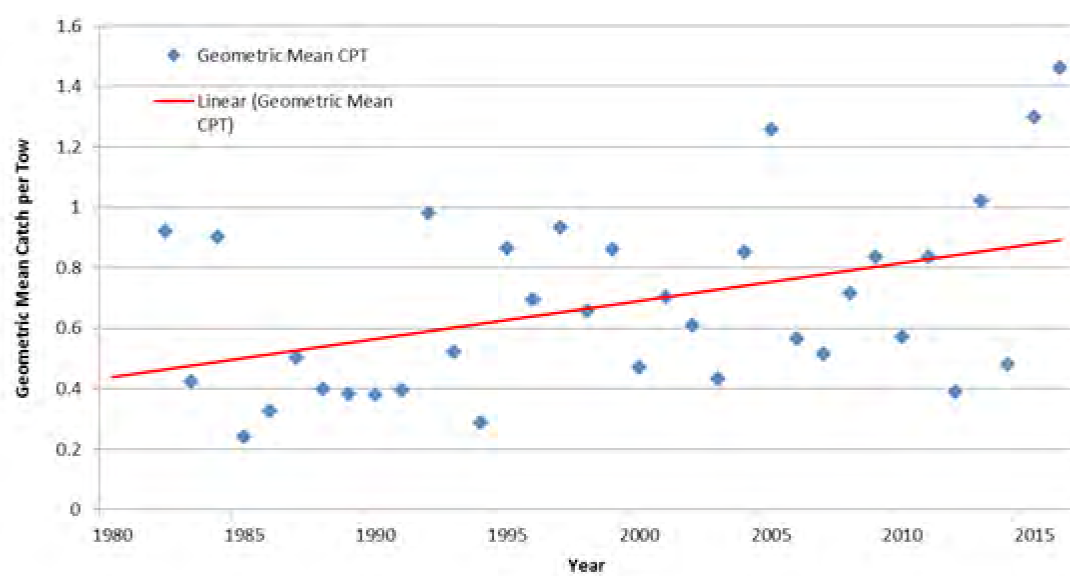

Figure 6.11.3 Index of relative abundance of American eels in the tidal Delaware River, based on catch per tow at 13 stations from April-June annually. The index is the geometric mean catch per tow. The predicted line was fitted as a linear regression, P = 0.01, R2 = 18.3%.

so-called silver eel stage, which are adults migrating down river and out to spawn in the Sargasso Sea. Smiley (1884) described "hundreds of traps" in the River between Lackawaxen, PA and Hancock, NY. The relatively high number of fishing weirs would suggest much heavier fishing mortality occurred on silver eels many decades ago. In recent years, nine weirs have been operating in the Delaware River, in New York. Due to the panmictic nature of the American Eel population, high fishing mortality in the upper Delaware River may not affect the number of new recruits arriving from the Sargasso Sea annually.

6.11.5 Future Predictions

There are no apparent bases for future predictions, but the coast wide nature of the spawning aggregation suggests that even if the Delaware Estuary spawning numbers would decline, the Estuary could still receive relatively high levels of annual recruits.

6.11.6 Actions and Needs

Although the main stem of the Delaware River is un-dammed, hundreds of dams still block passage along its tributaries; many are low-head dams under private ownership and in poor operating condition. In addition, there are thousands of culverts for roads that cross the tributaries. And in many areas the riparian forested buffer along the streams has been removed, leaving the stream exposed to sun and dramatically increased non-point source sediment and pollution run off. Fish passage and riparian restoration would help improve habitat for eel by increasing connectivity and improving in-stream habitat by providing shade and structure in these tributaries.

6.11.7 Summary

Eel populations in the Estuary declined in the late 1980s and increased in the mid-2000s. This increasing trend has continued through to 2016. Annual recruitment in Delaware has been well above average for the past four years. Harvest controls put in place through interstate management of the resource should bode well for sustainability of the fishery. Habitat initiatives such as dam removal, when practical, open up quality habitat in the upper portions of Delaware River tributaries.

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Suggested Citation for this Chapter

Zimmerman, J. 2017. "Chapter 6.11 - American Eel" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 278-282.

6.12 Macroinvertebrates

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Reprinted from Partnership for the Delaware Estuary. 2012. Technical Report for the Delaware Estuary and Basin. P. Cole, A. Padeletti, D. Kreeger (eds). PDE Report No. 12-01. 255 pages.

6.12.1 Introduction

Freshwater benthic macroinvertebrates (Fig 6.12.1) are a useful indicator of the ecological integrity of the Delaware River watershed for several reasons. A variety of macroinvertebrates live in every aquatic environment, and they are functionally important in several ecological roles. They are widely acknowledged to be good indicators of water quality because they are directly impacted by changes in water quality. Furthermore, they have been studied extensively in all parts of the Delaware River Basin.

In spite of these facts, it is difficult to aggregate and summarize data about this indicator for a multi-state area like the Delaware River Basin. This is because the various organizations that produce data (including state environmental agencies) all use different methods of sampling and analysis. Because of the differences in methods, only an approximate comparability between the data from different sources can be assumed. The best that can be done is take advantage of the fact that all states distill their findings into grades of condition (e.g. good, fair, poor). Assuming a rough comparability between these grades of condition, data from various sources can be brought together and presented side-by-side to approximate a basin-wide assessment.

An explanation of how this complex situation came about may help explain what this indicator tells us about the ecology of the Delaware River Basin broadly. The discussion may also help readers to appreciate something about benthic macroinvertebrates and their importance, and to understand more about the way environmental agencies perform water quality management in the United States.

6.12.2 Description of Indicator

The word "benthic" indicates animals that live on, or in, the substrate at the bottom of a waterbody. The word "macroinvertebrates" designates invertebrate animals that are large enough to be seen without the aid of magnification. In aquatic habitats, benthic macroinvertebrates are a broad group of organisms representing several phyla. The group includes roundworms, flatworms, mollusks, and several kinds of arthropods. Insects are a particularly important class of animals in the group, because of their abundance and diversity in the freshwater biota.

To be more precise, the indicator being discussed here is freshwater benthic macroinvertebrates that live in streams. Thus, those macroinvertebrates that live in lakes, ponds, wetlands, and tidal waters are excluded. These distinctions are primarily made because the nature of the information most easily available, is mostly for "wadeable" streams. Wadeable streams are relatively easy to survey, and these smaller waterbodies are where most states have focused their sampling efforts.

Most states have been sampling and compiling data about benthic macroinvertebrates since the 1970s or 1980s. The reason lies in what these animals say about the water quality of the environments in which they live. Using a procedure called "bioassessment," the biological condition of macroinvertebrate communities is analyzed to provide information about pollution and other water quality problems. In most states, bioassessment is used for multiple purposes, but the most widespread application of bioassessment is for

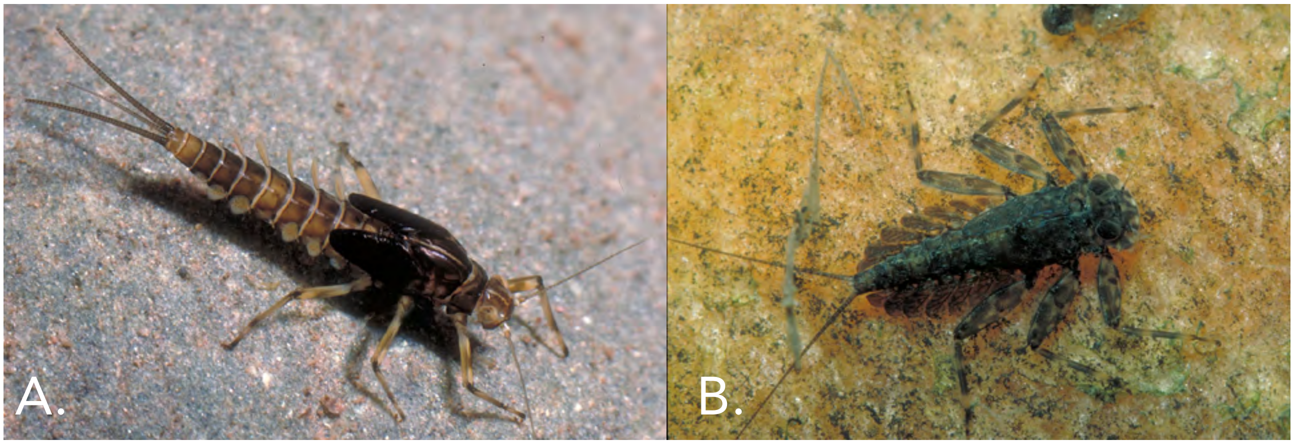

Figure 6.12.1 Mayfly larva, genera: A) *Baetis* and B) *Epeorus*. Photos credit: David H. Funk

the purpose of assessing a state's streams for the attainment of water quality standards. This program of assessment follows from the states' obligations under the Federal Clean Water Act.

The Federal Clean Water Act (and its amendments through 1987) requires states to develop water quality monitoring programs. States report to the U.S. Environmental Protection Agency (USEPA) on the quality of their waters using the biennial "305 (b) report" and the "303 (d) list." In most states, these biennial reports are now usually merged into a single document called the "Integrated Assessment" or the "Integrated List." The states are charged with assessing their waterways' conditions for various water uses, including, for example, public water supply, recreation, or aquatic life. The condition of macroinvertebrate communities is usually connected specifically to aquatic life uses. Results of bioassessments are used to determine if a waterway is "attaining" or "not attaining" the State's water quality standard, a threshold condition determined by the state.

Over the past 20 to 30 years, bioassessment has become increasingly important to environmental agencies, as advances have been made in the scientific understanding of water pollution and its effects. It is now widely acknowledged that biological indicators represent an essential means of determining the condition of natural waters. Some of the reasons for this are:

- Bioassessments provide information that is directly relevant to the goals of water pollution law (that is, that waters should be able to support aquatic life)
- Bioassessments provide information about long-term, chronic, or episodic stressors that are otherwise difficult to monitor.
- Bioassessment methods can be used to assess fish or periphyton (algae) in addition to macroinvertebrates. However, macroinvertebrates may be the most broadly useful of these biological groups, for reasons that include the following:
  - Macroinvertebrates are relatively easy to sample and analyze,
  - Macroinvertebrates are less mobile than fish, and thus they provide a better representation of the condition of a particular location, and
  - Macroinvertebrates are abundant and utilize diverse niches, which allows for a detailed determination of their condition over a wide gradient.

A bioassessment protocol is a set of standard practices describing how streams should be surveyed to produce data about ecological condition. Methods of collection and analysis must be standardized and consistently applied if data are to be comparable. However, there is no single macroinvertebrate protocol that is universally applicable in all circumstances. Natural variation sometimes dictates that protocols should differ, for the assessment of streams from substantially different environments. In addition, the needs and resources of the organization doing the sampling sometimes determines what protocol will be applied, since there are some protocols that demand more time and resources, while others can be done more rapidly. While there are broad similarities between many of the protocols, they usually differ from one another in their various details. A brief discussion of some of the variables will illustrate the reasons for all of this complexity. Every macroinvertebrate bioassessment protocol must include a description of each of the steps listed below. Within each of these four steps, there can be variations in methodology, as indicated by the following discussion.

1. Sampling: According to most protocols for wadeable streams benthic macroinvertebrates should be sampled using hand-held nets. The bioassessment protocol specifies details such as the exact shape of the net, the size of the mesh, and how the net should be handled in a stream. The protocol describes how to select sampling sites in the field and how to combine the material from grab samples to make a composite. The protocol further specifies how many organisms are needed to make a representative sample (typically between 100 and 300 individuals), and provides techniques for ensuring that those organisms are picked from the sample using an unbiased randomization method.

2. Identifying organisms: The bioassessment protocol specifies whether a collection of organisms will be identified in the field and returned to the stream alive, or preserved and identified in a laboratory. Field methods usually involve family-level identification, while laboratory methods often provide for identification to genus or to species. Laboratory analysis requires more time and effort, but provides more information. Whether the identification is done in the field or the lab, the product of this step is a list of the macroinvertebrate taxa found at a site, along with the number of individuals of each taxon.

3. Applying bioassessment metrics: The list of organisms produced in the previous step is analyzed by applying bioassessment metrics. This involves various methods of grouping and counting the organisms by types (by taxa). A variety of bioassessment metrics have been presented in scientific literature. Some metrics involve counting the number of different taxa found in a sample (assessing sample diversity); while other metrics involve counting the number of individuals of certain taxa or in certain groups of taxa (assessing community structure). Applying metrics often requires grouping taxa together by what is known about their ecological roles or characteristics. For example, there are several commonly-used metrics that take into account the relative "pollution tolerance" of the various taxa. Applying any metric to the list of taxa for a sample produces a numerical score. It is generally agreed that no single metric provides enough information to stand alone as a means of assessing water quality. Therefore, most states apply a suite of several metrics.

4. Applying an index: An Index of Biological Integrity (IBI) is a method of combining and integrating the information from several bioassessment metrics. It involves applying a series of mathematical transformations to each sample's metric scores and then combining them to give a single numerical index score. Typically, an index score for the so-called "reference condition" is developed using data from sites that are known to be undisturbed and that are judged to be appropriate reference sites based on regional and ecological considerations. Sample data are compared to reference conditions using the numerical scores calculated using the index. Increasing degrees of disturbance (or pollution) are indicated by scores that range further and further from the reference score. For state agencies, one of the main purposes of their bioassessment work is to identify those streams that are divergent enough from the reference condition that they are determined to be "not attaining" the state's

water quality standards for aquatic life use. Typically, the threshold that is used to determine attainment are linked to a particular numerical score using the appropriate index.

The "Present Status" and "Past Trends" sections of this chapter are based on data from five different sources, namely the four Delaware River Basin states and the Delaware River Basin Commission (DRBC). These five organizations all use different macroinvertebrate protocols in their programs for stream assessment. In addition to this interstate variability, there is also intrastate variability, because some states actually use more than one protocol to account for natural variation. A brief description is provided of how each of the organizations that contributed data has designed their respective programs for producing macroinvertebrate data.

Delaware Delaware is a small state with relatively little natural variability, but it does straddle a significant eco-regional divide. Delaware's land area is divided between the Middle Atlantic Coastal Plain eco-region and the Northern Piedmont eco-region. In the Coastal Plain, where streams have a low-gradient character, the state's bioassessment program specifies the use of the protocol developed by an USEPA-sponsored, multi-state workgroup called the Mid-Atlantic Coastal Streams Workgroup (USEPA 1997). In the Piedmont, the state specifies the use of methods documented in USEPA's 1999 Rapid Bioassessment Protocols report (Barbour et al. 1999). The structural and ecological differences between coastal plain streams and piedmont streams dictate several differences between the two protocols. For both stream categories, Delaware specifies that macroinvertebrate samples are to be preserved and identified in a laboratory, with most taxa identified to genus. Both protocols also utilize a multi-metric index. Of the assessment stations that make up the data set for Delaware's Delaware Estuary Basin, 46% are from the Piedmont and 54% are from the Coastal Plain.

Pennsylvania In 2006, after 10 years of effort, Pennsylvania completed their first statewide bioassessment survey, which was done using a modified version of the USEPA Rapid Bioassessment II Protocol from the document referenced above (Barbour et al. 1999). This method used field identification of organisms and family-level taxonomy. At about the same time, the state decided to refine their biomonitoring program and implement major changes to the bioassessment protocols. Pennsylvania's new program is called the Instream Comprehensive Evaluation (ICE). In it, the State's streams are divided into three major ecological categories, each of which is assessed by a different protocol. Each protocol specifies particular sampling methods, and how metrics and index calculations should be applied. These protocols are briefly described below.

The largest group of streams in Pennsylvania is categorized as riffle-run streams, which are assessed using the "Freestone Streams" protocol. The method specifies making a certain number of collections from shallow gravel-bottom or cobble-bottom riffle habitat, and then compositing and randomly sub-sampling to give a 200-organism sub-sample. The sub-sample is preserved and identified in a laboratory to genus, and a multi-metric IBI is applied to the taxa list. The preferred seasons for sampling are between November and May, so as to avoid sampling during the summer emergence period of many important insects. However, a method for "Freestone Streams, Summer Samples" is also available, for when agency workload requires that stream assessments continue through the summer months. The "Summer Samples" method provides a modified analysis to account for the effects of seasonal emergence on the invertebrate community. (During the summer months, many insects emerge as winged adults, and their aquatic forms are notably absent from stream-collected samples. In light of this, practitioners of bioassessment have two choices. They may avoid sampling during the time of year when the benthic community is likely to be altered by emergence, or they may develop protocols that are specifically tailored to each particular seasonal condition.) Freestone Streams account for 91% of the assessments performed in Pennsylvania's Delaware River Basin.

Pennsylvania's second stream category is the low-gradient streams that are lacking in riffle habitat. Pennsylvania uses the phrase "Multi-Habitat" to refer to this stream category and protocol. For Multi-Habitat sites, the sampling methods are designed to provide a means of capturing representative organisms from several specific kinds of habitats (including, for example, coarse submerged debris, submerged aquatic vegetation, and deposits of coarse particulate organic matter). A specific multi-metric analysis and IBI are applied. This category is somewhat similar to the Mid-Atlantic Coastal Plain Streams "Coastal Plain" streams discussed above in the "Delaware" section, as well as to the "Coastal Plain (Non-Pinelands)" category discussed below in the "New Jersey" section. However, the analogy is not exact, because many of Pennsylvania's Multi-Habitat sites are not in the coastal plain but in low-gradient topography in plateau regions, such as the Pocono region of northeast Pennsylvania. Multi-Habitat assessments account for 7% of the assessments performed in Pennsylvania's Delaware River Basin.

The third category of streams, limestone streams, is assessed using the protocol for '"True" Limestone Streams.' This method is specifically for spring-fed streams with high alkalinity and constant year-round temperature. These streams are considered ecologically unique and are important as cold-water fish habitat. The protocol specifies the collection of two samples from riffle habitat, composited and sub-sampled to make a 300-organism sample, followed by laboratory-identification of organisms to genus. A specific multi-metric analysis and IBI are applied. Limestone Streams account for 2% of the assessments performed in Pennsylvania's Delaware River Basin.

New Jersey From the early 1990s through 2008, New Jersey's biennial Integrated Assessment reports were based on a type of Rapid Bioassessment Protocol that used family-level taxonomy. During this period, all of the state's freshwater streams were assessed using the same index, which was known as the "New Jersey Impairment Score" (NJIS). However, like Pennsylvania, New Jersey revised their bioassessment program in the 2000s to make it more technically rigorous. Stream assessments are now based on genus-level taxonomy; and three different protocols are used, according to the major ecoregions of the state. The three protocols are: the High Gradient Macroinvertebrate Index (HGMI), which applies to the streams of Highlands, Ridge and Valley, and Piedmont ecoregions; the Coastal Plain Macroinvertebrate Index (CPMI), which applies to the Coastal Plain excluding waters considered Pinelands waters; and the Pinelands Macroinvertebrate Index (PMI), which applies to Pinelands waters. Each of these three protocols has particular sampling methods, assessment metrics, and an index. In the network of assessment stations for New Jersey's Delaware River Basin, 44% of stations are assessed by the HGMI, 37% by the CPMI, and 19% by the PMI.

New York New York's biological monitoring program began in 1972, with the first surveys done on the state's large rivers, using artificial substrate samplers. Since 1984, New York has used a "Rapid Assessment" method in the state's wadeable streams, for both special studies and as part of the statewide ambient water quality monitoring program. In 1987, the statewide program was re-designed to use a rotating cycle of monitoring and assessments called Rotating Integrated Basin Studies (RIBS). Under the current RIBS schedule, chemical and biological monitoring is conducted in all of the state's 17 major drainage over a five-year period. Riffle habitat is targeted for biological sampling of wadeable streams. Non-wadeable waters are monitored using artificial substrate samplers. The index period for wadeable stream sampling is from July through September. Individual metrics characterizing the benthic macroinvertebrate community are combined to form a multi-metric index called the Biological Assessment Profile. There is no differentiation of streams by eco-region; however, modification of the sampling methods and assessment metrics are used for low-gradient, sandy-bottom streams. Samples are preserved and identified in the laboratory to genus or species.

DRBC As an interstate agency, DRBC takes responsibility for assessing the mainstem Delaware River where it forms a border between states. Since 2001 DRBC has collected benthic macroinvertebrate samples annually at about 25 fixed sites on the Delaware River. These sites range from Hancock, NY (river mile 331/533 km) to just above the head-of-tide at Trenton, NJ (river mile 137/220 km). All samples are collected from gravel- or cobble-dominated riffle habitats. Sampling generally occurs in the late summer, with the central sampling window being August and September. The samples are preserved for laboratory identification, and the organisms are generally identified to genus. The analysis methodology used for the 2010 Integrated Assessment is based on a multi-metric IBI with a 100-point range. In their Integrated

Assessment report, DRBC discusses how these numerical results can be graded for the purpose of assessing attainment of water quality standards, but they also indicate that this analysis is preliminary. The agency plans to refine it with additional data and additional statistical work.

6.12.3 Present Status

For this Technical Report, the status of macroinvertebrates in the nontidal Delaware River Basin is determined using the data produced by the States for their biennial water quality reporting. All four basin states and DRBC report results of water quality monitoring to USEPA for the biennial 303(d) list, sometimes called the Integrated List of Waters, or the Integrated Assessment. For this Technical Report, the states have provided the most recent bioassessment data they were able to share, and for the most part it comes from the data that they used to prepare the 2010 Integrated List. Some state-by-state details are given in the sections below, and in the accompanying figures.

Delaware Present status is given by data from 87 individual assessments, performed between 2006 and 2009. Four grades of condition are reported: excellent condition, good condition, moderately degraded, and severely degraded. The aggregated data are presented in figure 6.12.2, figure 6.12.3, and figure 6.12.4.

Pennsylvania Present status is given by data from 914 assessments, spanning more than 10 years of time. Each station is reported as either "attaining" or "not attaining" the state-determined regulatory threshold for aquatic life use. The aggregated data are presented in figure 6.12.5., figure 6.12.6, and figure 6.12.7.

New Jersey Present status is given by data from 301 stations. The statewide program Ambient Biomonitoring Network (AMNET) has produced several rounds of survey results for each of the state's major basins. However, the current survey, known as AMNET Round 4, is not yet complete, and the NJ Department of Environmental Protection (NJDEP) was not able to share the unfinished data for the Lower Delaware River Basin. Therefore, this report presents recent data (AMNET Round 4, performed between 2007 and 2012) for only the Upper Delaware River Basin (141 stations), and older data (AMNET Round 3, performed between 2002 and 2007) for the entire Delaware River Basin (301 stations). Four grades of condition are used: excellent, good, fair, and poor. The aggregated data are presented in figure 6.12.8, figure 6.12.9, figure 6.12.10, figure 6.12.11, and figure 6.12.12..

New York Present status is given by data from 78 stations, collected 10 years. Four grades of condition are reported: non-impacted, slightly impacted, moderately impacted, and severely impacted. The aggregated data are presented in figure 6.12.13, figure 6.12.14, and figure 6.12.15.

DRBC Present status is given by data from 23 stations, collected in 2008 and 2009. Stream condition is given as a numerical score according to the IBI that the agency uses. The aggregated data are presented in figure 6.12.16. (Certain stations sampled by DRBC are not included in this figure because they were not sampled throughout the entire period.)

Considering the Delaware River Basin as a whole, it appears that there may be some broad regional conclusions that can be drawn from the bioassessment data. New York is the state with the lowest percentage of low-scoring stations, and apparently the best overall condition. Delaware is the state with the highest percentage of low-scoring stations; and New Jersey and Pennsylvania are in between.

For the three states whose bioassessment programs include multiple ecoregional indices, a comparison of the ecoregional differences shows somewhat similar trends in each state. The analogous categories of Piedmont (Delaware), Freestone (Pennsylvania), and High-Gradient (New Jersey) have somewhat better conditions than the corresponding low-gradient categories: Coastal Plain (Delaware and New Jersey) and Multi-Habitat (Pennsylvania). These observations suggest that the condition of benthic macroinvertebrates is generally better in the upper portions of the Delaware River Basin, farther from the coast, and closer to

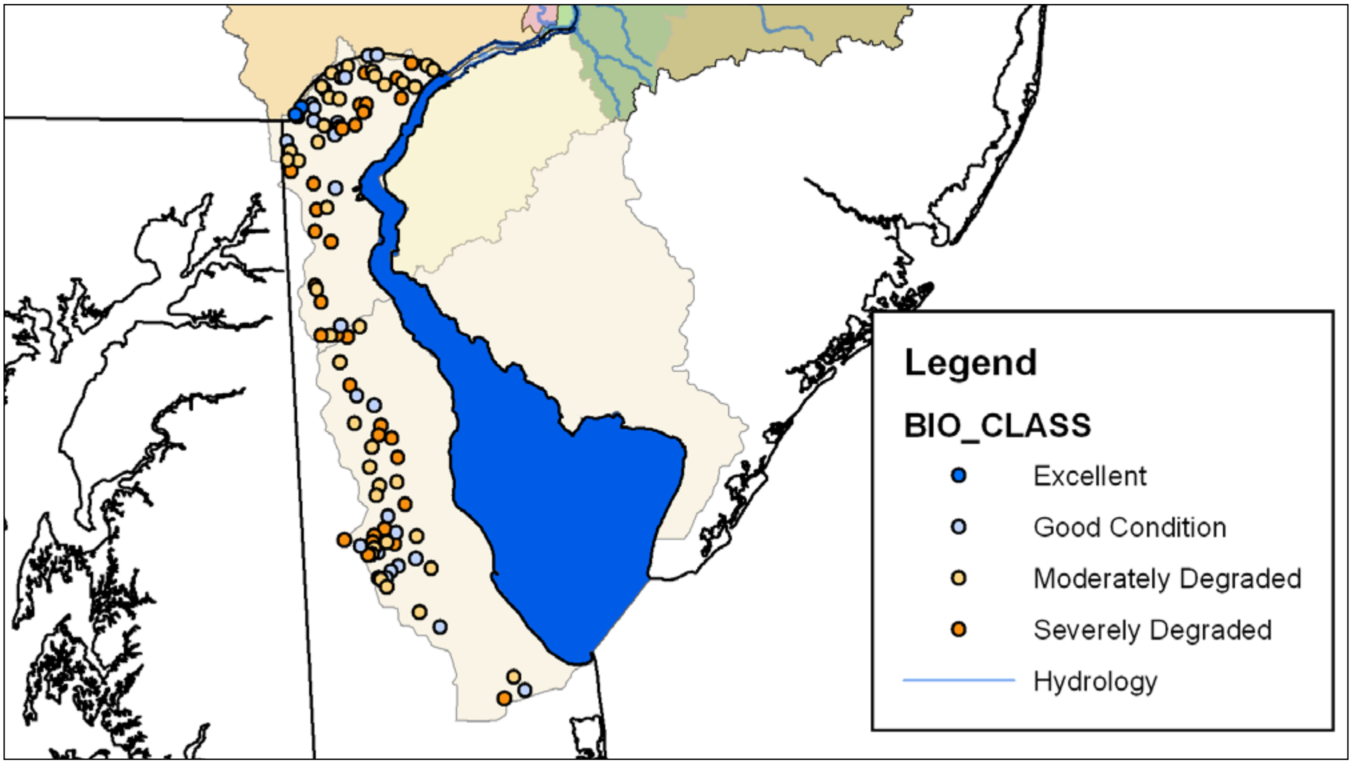

Figure 6.12.2 Delaware's Delaware Estuary Basin: map showing the locations of macroinvertebrate bioassessment stations.

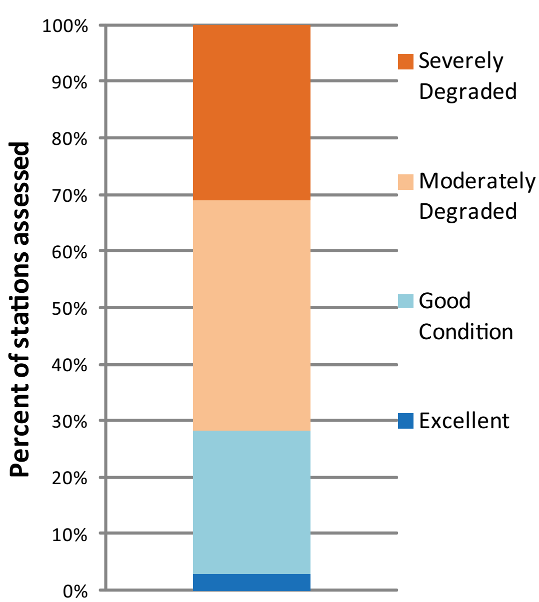

Figure 6.12.3 Bioassessment Station Data for Delaware's Delaware Estuary Basin.

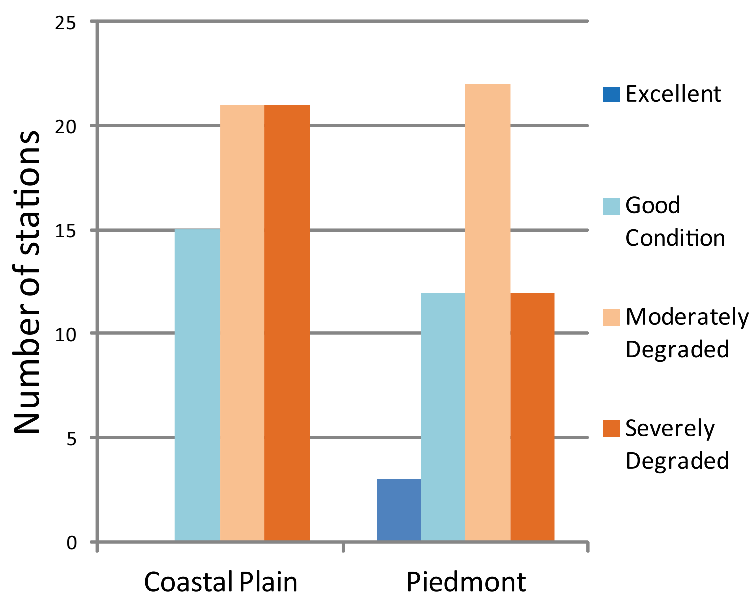

Figure 6.12.4 Bioassessment station data for Delaware's Delaware Estuary Basin, Data grouped by Eco-Region/Index (87 stations).

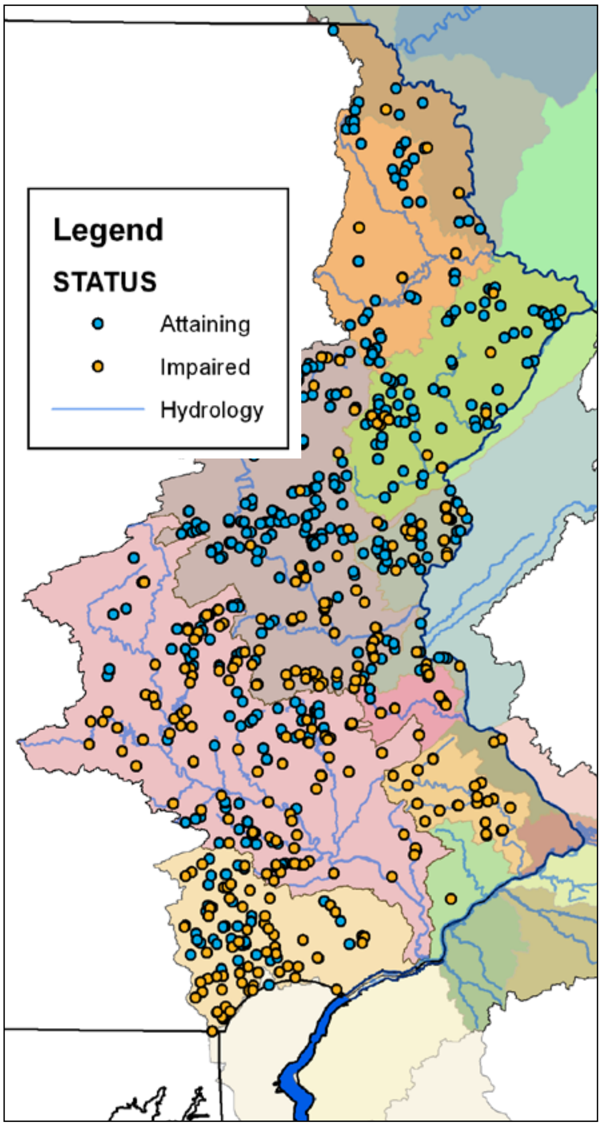

Figure 6.12.5 Pennsylvania's Delaware River Basin: Map showing the locations of macroinvertebrate bioassessment stations.

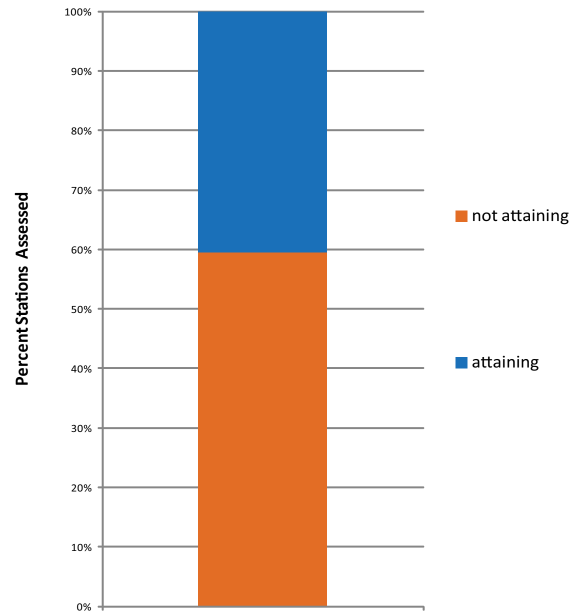

Figure 6.12.6 Bioassessment Station Data for Pennsylvania's Delaware River Basin (914 stations).

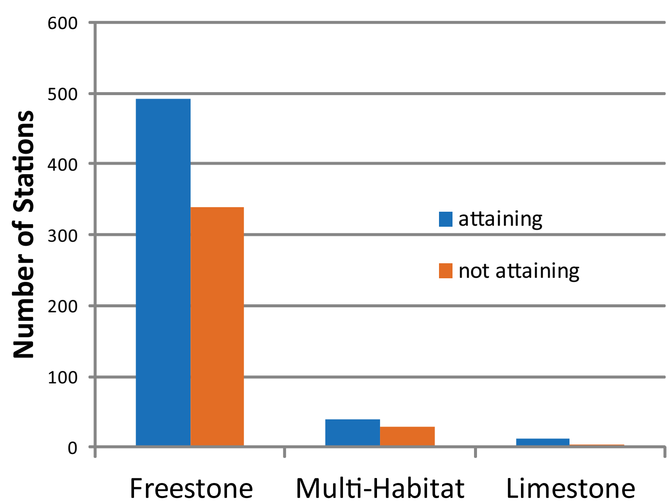

Figure 6.12.7 Bioassessment Station Data for Pennsylvania's Delaware River Basin, Grouped by Eco-Region/Index (914 stations).

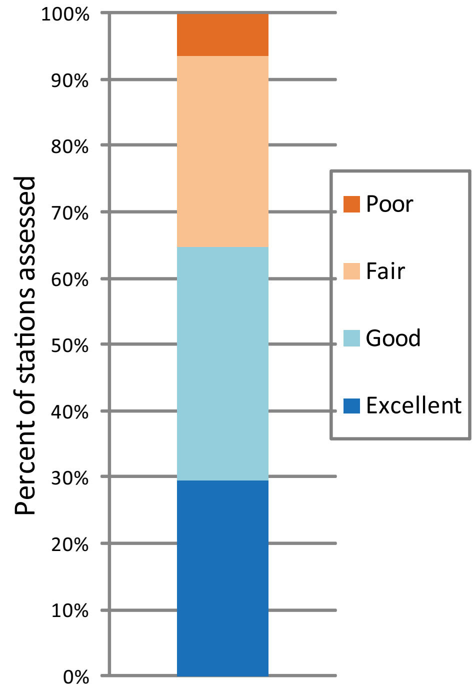

Figure 6.12.9 Bioassessment Station Data for New Jersey's Delaware River Basin, AMNET 4 Survey with 141 stations (2007-2012).

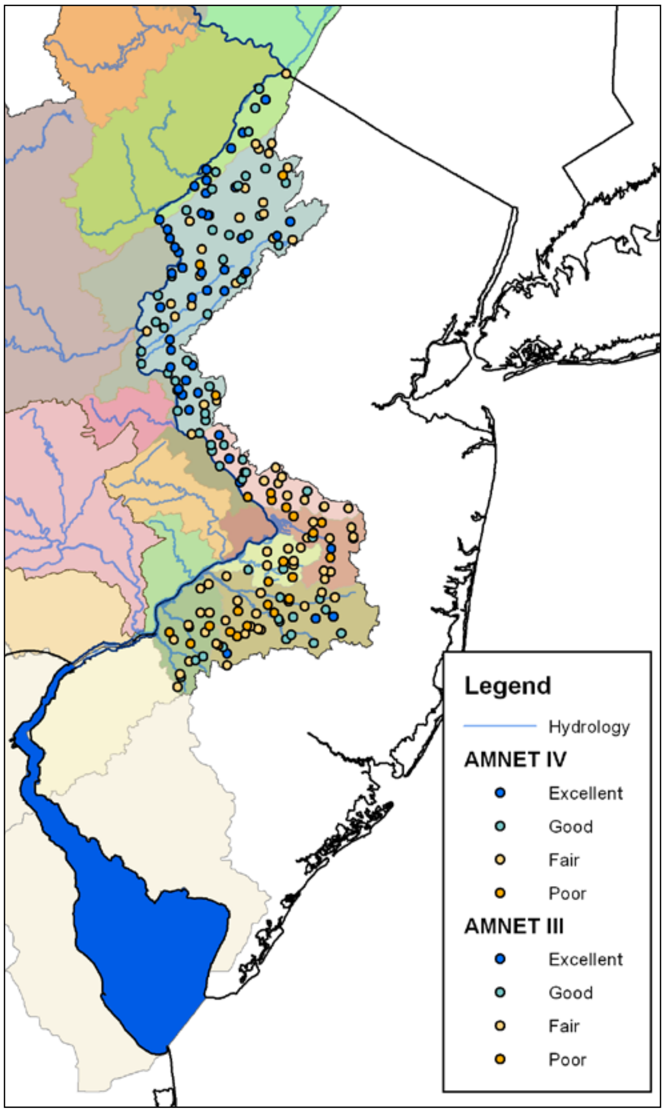

Figure 6.12.8 New Jersey's Delaware River Basin: Map showing the locations of macroinvertebrate bioassessment stations

Figure 6.12.10 Bioassessment Station Data for New Jersey's Delaware River Basin, AMNET 3 Survey with 301 stations (2002-2007).

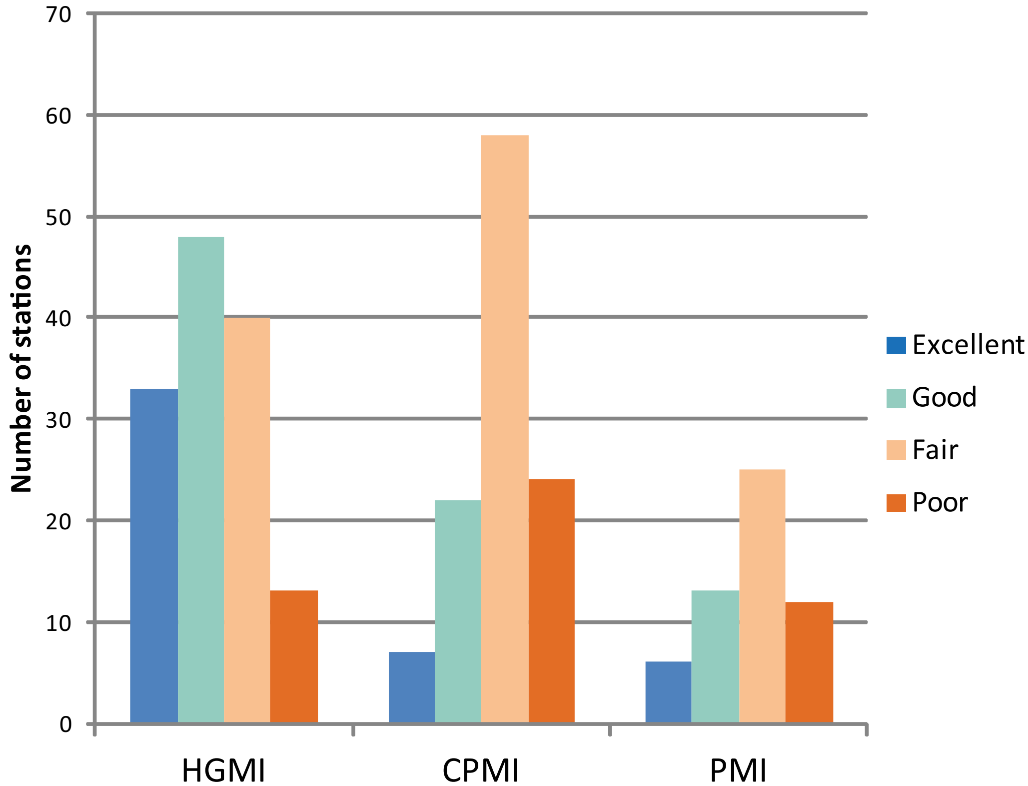

Figure 6.12.11 Bioassessment Station Data for New Jersey's Delaware Basin, Data Grouped by Eco-Region/Index (301 stations).

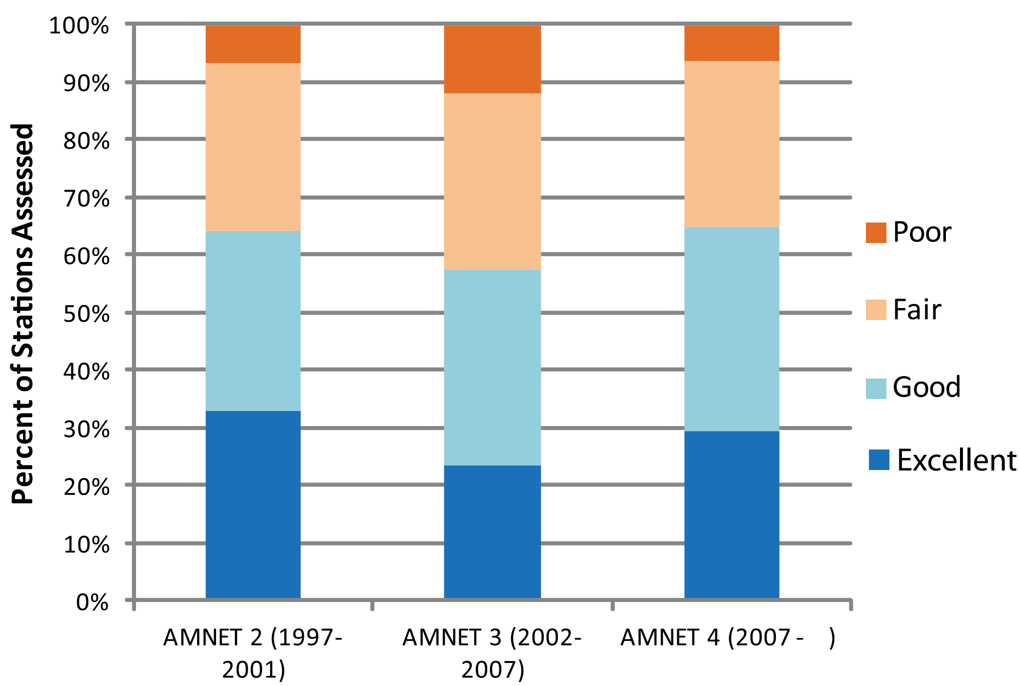

Figure 6.12.12 Bioassessment Data for Three Successive Surveys of New Jersey's Upper Delaware Basin (approximately 140 stations).

"headwaters." This corresponds to what may be expected based on a general understanding of water quality problems in this Basin. Good water quality is generally expected (hence macroinvertebrate quality) to correlate negatively with urban land cover, which is mostly in the Lower Basin, and positively with forested land cover, which is mostly in the Upper Basin.

The data suggested the above conclusions, as if the data was from a basin-wide survey, however this is not exactly the case. The data presented in this report, particularly for the states of Delaware and Pennsylvania, may not represent a random selection of sites, as would have been ideal if this had truly been a basin-wide survey of ambient conditions. In Pennsylvania this is due to the fact that the state has not yet completed a full survey of the Basin using their revised bioassessment protocol. In Delaware, the available data is skewed towards lower-quality waterways, which were prioritized for monitoring in recent years.

Benthic macroinvertebrate community condition is affected primarily by water quality and habitat disturbance. There are many reasons why conditions at a particular site may appear to be degraded. Furthermore, the Basin being discussed is large and diverse. For these reasons, it would probably be inappropriate to draw further conclusions from the data presented. When biomonitoring results cause a state agency to list a stream as "impaired," the agency is supposed to attribute the impairment to a "source" and a "cause." The Integrated List for each state contains information about these "source" and "cause" determinations for each listing, but the terminology that is used is complex. Because of this complexity, an attempt was not made to gather or analyze "source" and "cause" information for the present report. Readers who are interested in examining the sources and causes of impairments listed by the states are referred to the Integrated List documentation for each of the states.

6.12.4 Past Trends

Monitoring of trends is one of the stated goals of the biomonitoring program in most of the states. However it is more easily said than done. Reporting trends is difficult at the present time, because of the nature of the available data. In Delaware and Pennsylvania, sufficient data was not obtained to present any kind of trend. Several more years of work will be necessary before meaningful time series will be generated for Pennsylvania and Delaware.

We can discuss trends for New Jersey, New York, and for the mainstem Delaware River (DRBC data), based on the collected data.

New Jersey New Jersey's AMNET program has completed several rounds of sampling at an established set of stream stations. Round 2 of the AMNET program was performed between 1997 and 2002, round 3 between 2002 and 2007, and round 4 began in 2007 and is still unfinished. (There was a round 1 in the 1990s, but it was not as comprehensive as the subsequent surveys, and cannot be compared with the others on a station-by-station basis.) Although results for AMNET rounds 2 and 3 were originally reported using the NJIS index, the NJDEP was able to re-analyze the original data from those surveys using the more detailed taxonomy of the new indices. They have prepared a table which shows condition assessments for 144 stream stations in the Upper Delaware River Basin for these three rounds of survey. (The agency's analysis of data for the Lower Delaware River Basin for AMNET 4 is still incomplete.) These Upper Basin results are presented in aggregate in our figure 6.12.12.

Based on the data as shown in figure 6.12.12, the general condition of benthic macroinvertebrates in the streams of New Jersey's Upper Delaware River Basin appears to have fallen slightly between round 2 and round 3, and then improved again in round 4. However, it would be inappropriate to draw firm conclusions from such a limited set of data. In fact, the data do not necessarily indicate a general degradation of conditions between rounds 2 and 3, followed by a recovery. Instead, it seems likely that the apparent differences between these respective surveys may be within the range of variation that can be expected for repeat applications of the bioassessment method.

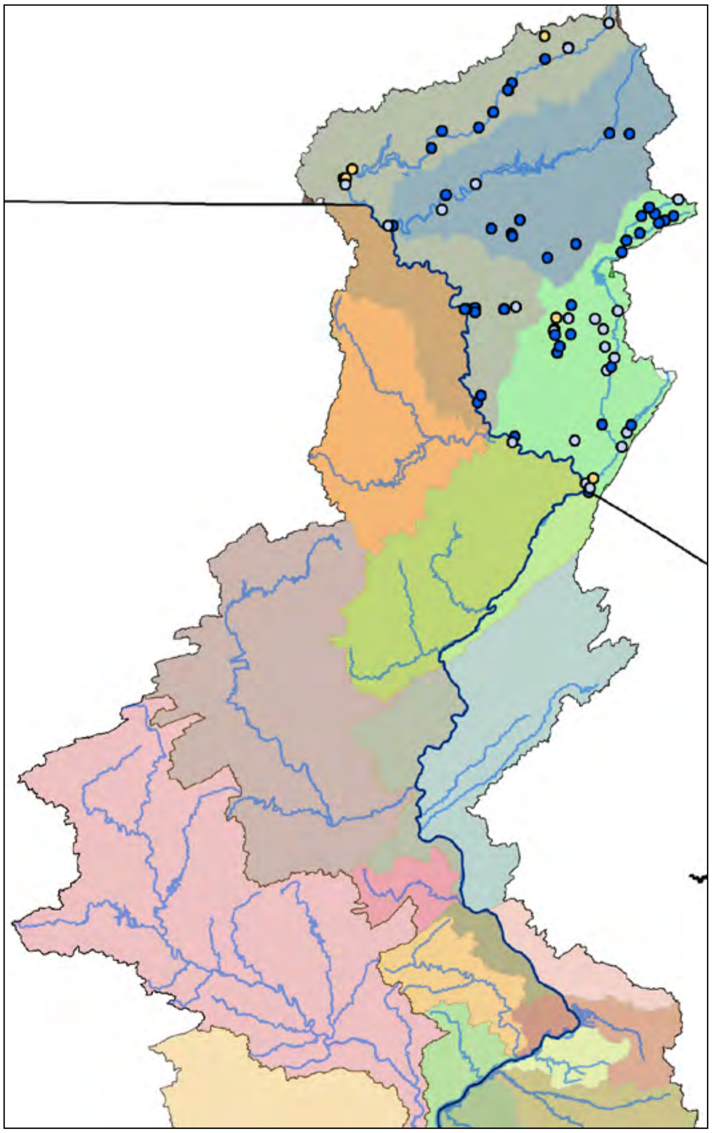

Figure 6.12.13 New York's Delaware River Basin: Map showing the locations of macroinvertebrate bioassessment stations.

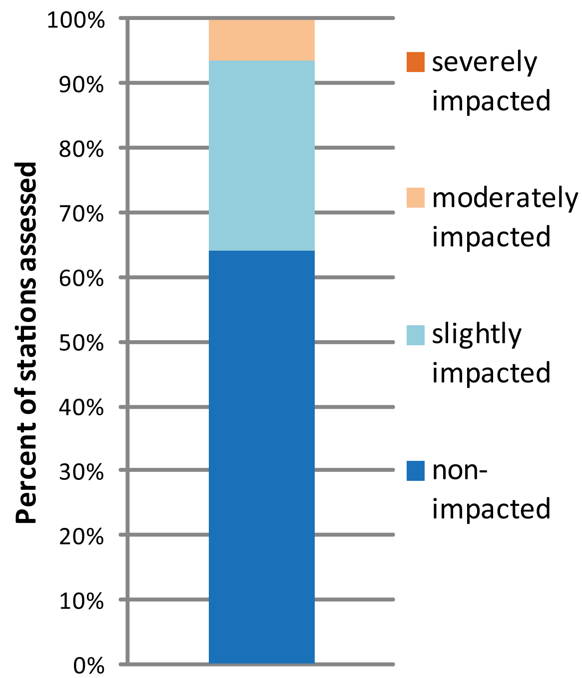

Figure 6.12.14 Bioassessment Station Data for New York's Delaware River Basin (78 stations).

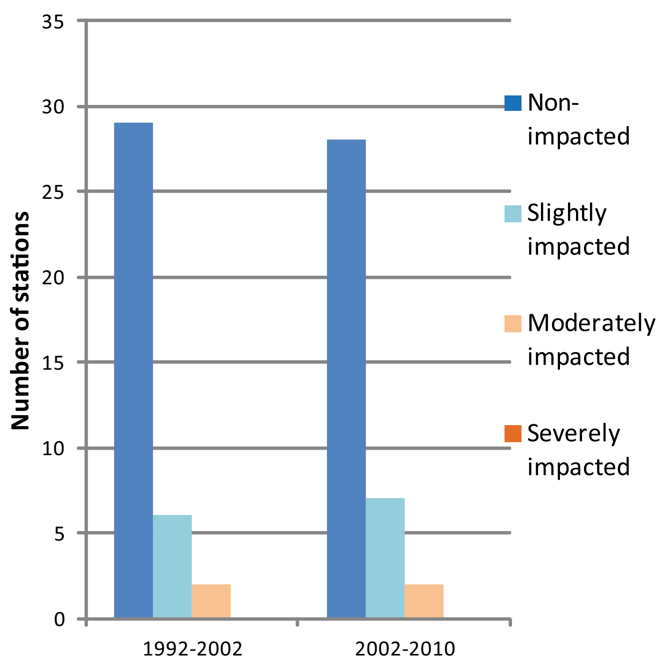

Figure 6.12.15 Bioassessment Station Data for New York's Delaware River Basin, comparing data from two successive decades (37 stations).

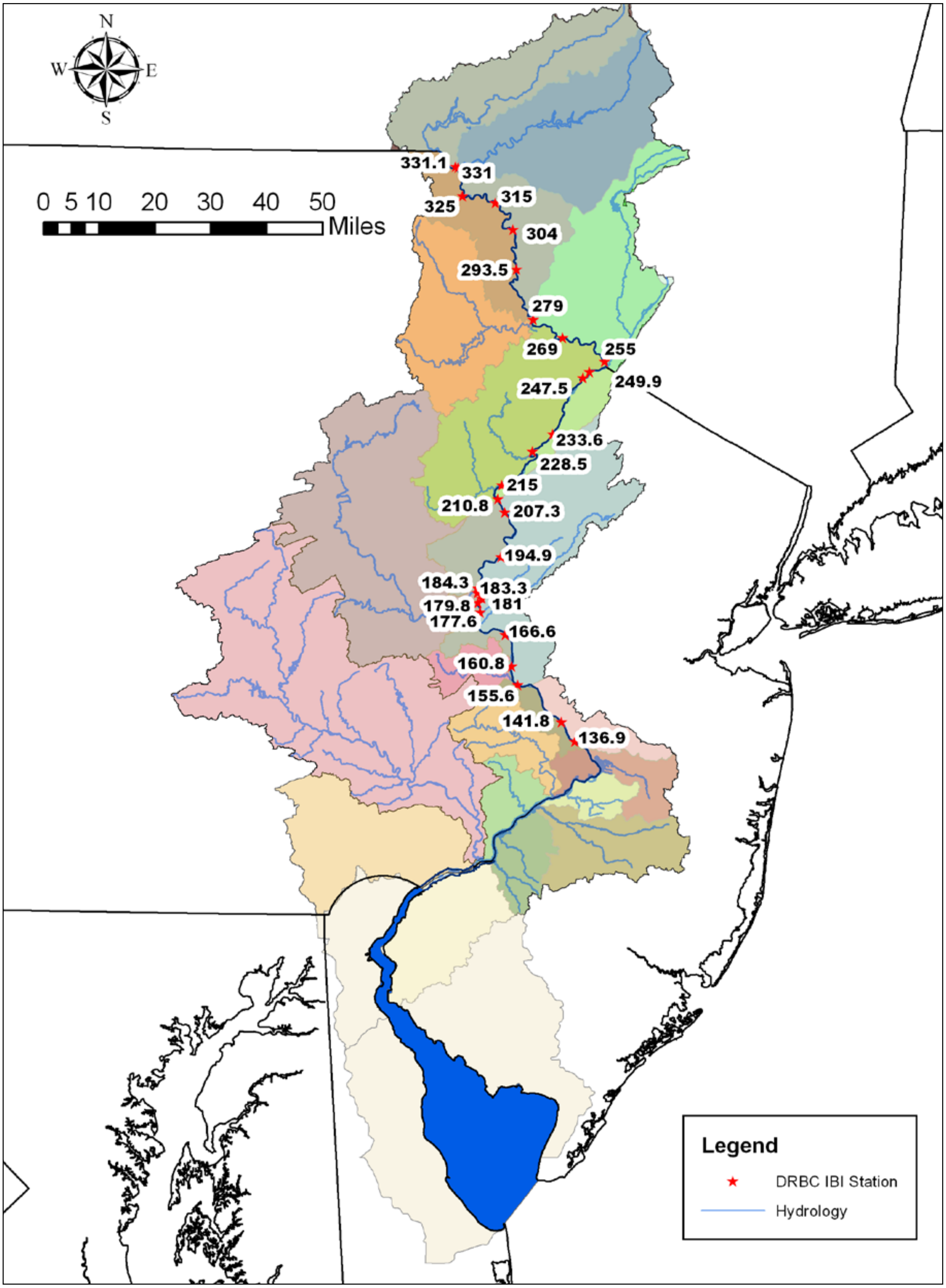

Figure 6.12.16 DRBC mainstem sampling locations.

New York Over the years, New York has collected multiple rounds of data for a certain number of stations in the Delaware River Basin. In 2004, the state published a report entitled "30-Year Trends in Water Quality of Rivers and Streams in New York State Based on Macroinvertebrate Data, 1972-2002." (The report is available on line at http://www.epa.gov/bioindicators/pdf/NYSDEC30yrTrendsReport.pdf). That report compared the results of surveys conducted between 1992 and 2002 to an earlier set of data collected before 1992.

For the present report, the recent data (2003 – 2010) was compared to the data from the 1990s that appears in the state's "30-Year Trends" report. The comparison reveals that the changes that occurred from the 1990s to the 2000s were very small. The total number of stations with assessment data in both decades was 37. Of those, 28 scored the same both times, while 9 scored differently. Five stations changed from "non-impacted" to "slightly impacted," and four others changed from "slightly impacted" to "non-impacted." Thus the overall difference in the Basin appears to be very small. Figure 6.12.15 presents this comparison as a chart.

DRBC Because DRBC's sampling team has returned to the same stations for several years on a regular basis, their data set appears to offer an opportunity to look at bioassessment data in a time series. Some of these data are presented as a chart in figure 6.12.17. Based on the data, there is year-to-year variability, but it appears that there are no clear trends.

DRBC's technical staff believe that some of the variability observed here can be attributed to particular events or conditions. It is thought that a severe summer drought or a major flood can affect aquatic life enough to produce anomalous scores using the bioassessment metrics and index. At least one example of this seems to be evident in DRBC's data. There is a noticeable drop in bioassessment index scores for 2006 at several stations along the River, which may be attributed to the effects of a major flood that occurred in late June of that year, shortly before the macroinvertebrate sampling was conducted (Personal Communication, Erik Silldorff).

6.12.5 Future Predictions

The future condition of the benthic macroinvertebrates in the Delaware River Basin can be expected to follow the various causes of waterway impairment. Any attempt to project future conditions in the Basin would be speculative, particularly in light of the challenges of determining past trends from macroinvertebrate data.

6.12.6 Actions and Needs

Bioassessment of macroinvertebrates is a well-established practice in state environmental agencies, and it may be expected to continue for the foreseeable future. Bioassessment has become a core element of the regulatory system for protecting water quality in the United States. Over time, it may be expected that the uses of bioassessment data will be refined as the datasets grow and as organizations gain experience with the interpretation of information produced.

The fact that the states all use different methods is frustrating to anyone who is interested in making interstate comparisons. At present, there is no particular movement towards requiring the standardization of methods. However, as states gather more data and gain a better understanding of how to use it, and with continued improvements in data management, there is reason to hope that meaningful interstate comparisons may become more readily available in time.

6.12.7 Summary

Benthic macroinvertebrates are a diverse and important natural resource. They are well known to people who are concerned with water quality and watershed health, but ignored or taken for granted by most people in the general public. Macroinvertebrates are not normally considered for specific management actions of any

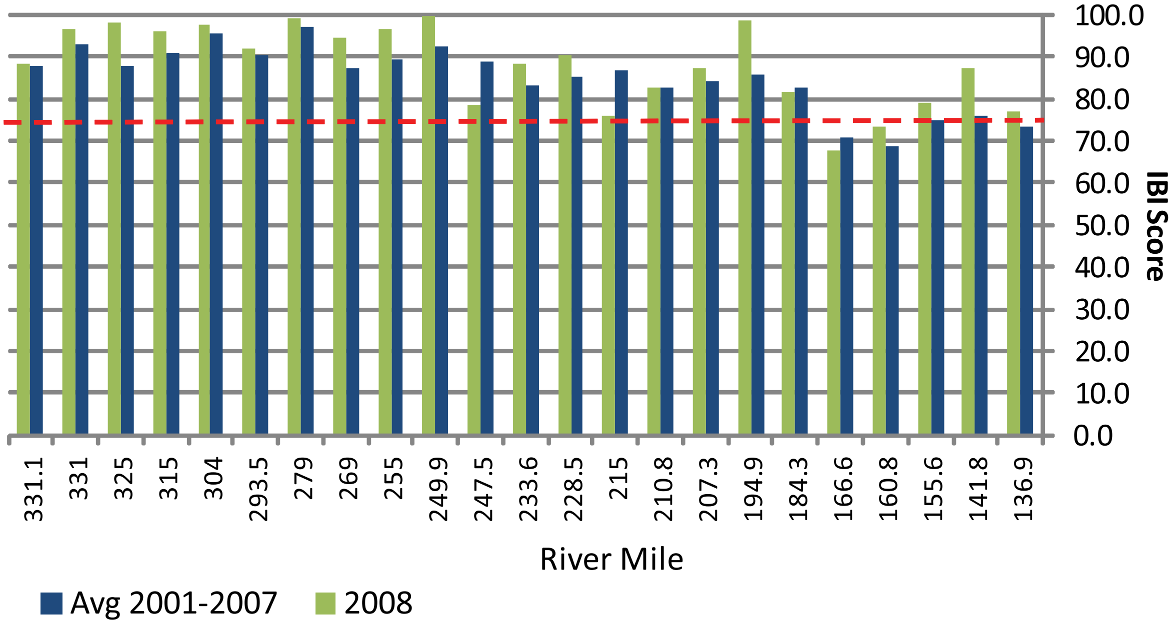

Figure 6.12.17 Bioassessment Station Data for Mainstem Delaware River By River Mile.

kind. The management actions that affect benthic macroinvertebrates are essentially the same management actions that affect water quality and aquatic habitats. It is expected that macroinvertebrates can be allowed to thrive by preventing water pollution and by protecting or restoring natural habitat conditions in waterways.

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Suggested Citation for this Chapter

Burke, D., G. Bright. 2012. "Chapter 6.12 - Macroinvertebrates" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 283-298.

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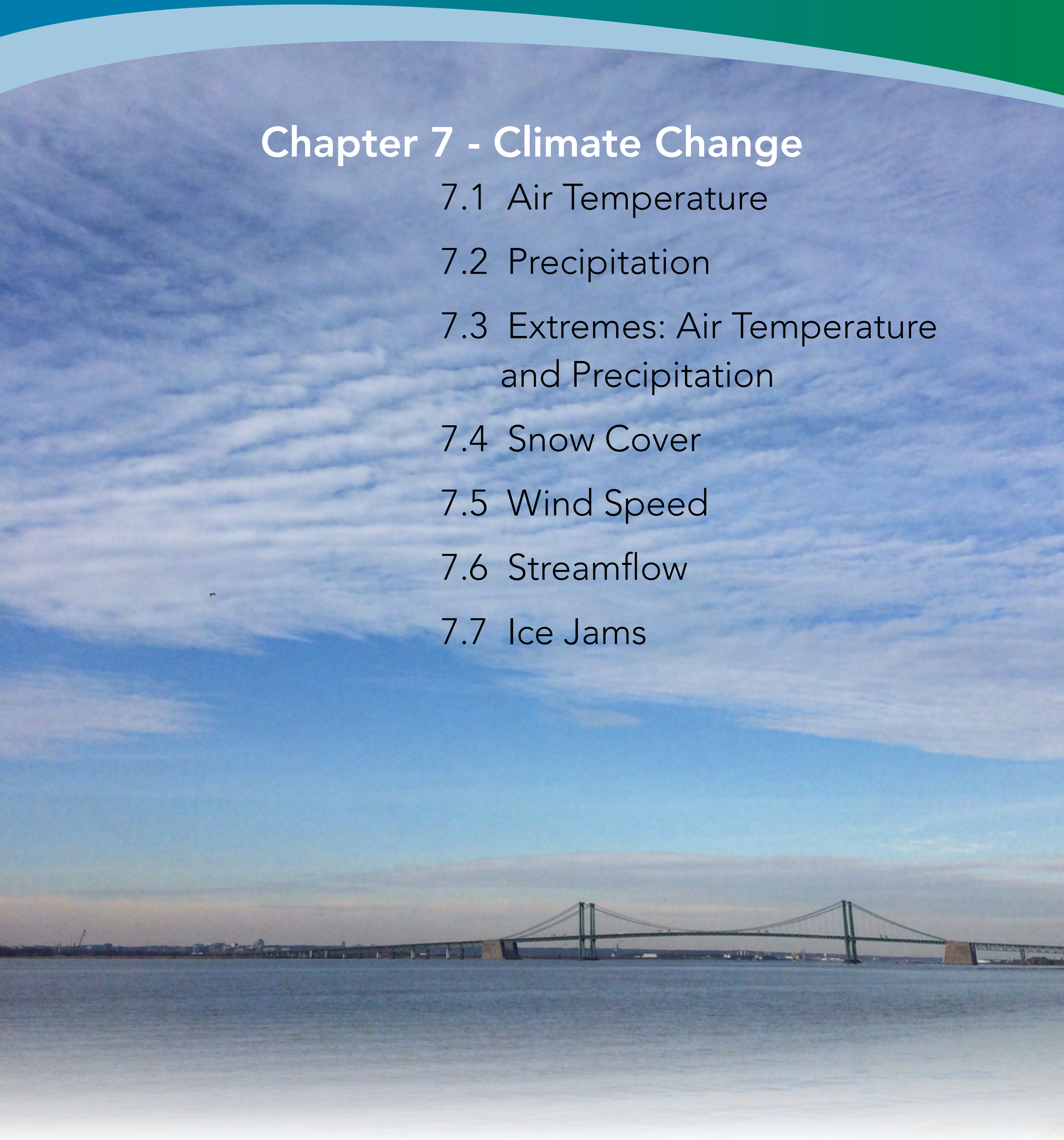
Chapter 7 - Climate Change



Partnership for the DELAWARE ESTUARY

December, 2017 | Report No.17-07

A publication of the Partnership for the Delaware Estuary—A National Estuary Program

7. Climate Change

Andrew Ross and Raymond Najjar
Pennsylvania State University

This chapter describes how the climate of the Delaware River Basin (DRB) has changed in the past and may change in the future. The focus is on air temperature and precipitation throughout the watershed with additional analyses of changes in snow cover, wind speed, and ice jams in the Delaware River.

All indicators presented in the previous report have been updated to use the most recent data available. All datasets and selected sites match those used in the previous report, aside from some minor differences. Trends in this report are calculated using a new, nonparametric method that accounts for autocorrelation (discussed next). Although different datasets and procedures were applied to analyze the different indicators, there were several common methods used in the analysis of most indicators. All trends were calculated using the nonparametric Theil-Sen slope estimator (Theil 1950; Sen 1968), and the statistical significance each trend was tested using the nonparametric Mann-Kendall test for trend (Mann 1945; Kendall 1955) with pre-whitening to reduce the impact of autocorrelation (Yue et al. 2002) at a significance level α =0.05. These statistical methods were provided by the R package "zyp" (Bronaugh and Werner 2013). Trends were calculated for both the full extent of each time series and for the most recent 30 years (1986–2015). To merge data from multiple stations into a single time series, anomalies were calculated by subtracting each station's 1981–2010 mean value prior to averaging the station data. Some of the indicator trends were broken down by season. The seasons were defined as December to February (DJF; winter), March to May (MAM; spring), June to August (JJA; summer) and September to November (SON; fall). Finally, for daily data (temperature and precipitation extremes and streamflow), if a year or season at a given station had more than 5 days of missing or flagged data in any month, the data from the entire year or season were excluded from the analysis.

7.1 Air Temperature

7.1.1 Description of Indicator

Monthly mean near-surface air temperature was obtained from version 2.5 of the U.S. Historical Climatology Network (USHCN) database (Fig 7.1.1). A complete description of the dataset and data processing is provided in Menne et al. (2009), Menne et al. (2015a), and Menne et al. (2015b); an abbreviated description is presented here. Most data in the USHCN are a subset of the data from the National Oceanographic and Atmospheric Administration's (NOAA's) Cooperative Observer Program (COOP). The COOP data stations included in the USHCN dataset are relatively long, stable, and amenable to adjustments for non-climatic changes (such as station relocations).

The COOP data consist of daily high and low temperatures. Daily mean temperature is computed as an average of the daily high and low temperature. During processing for inclusion in the USHCN dataset, the data are extensively screened for erroneous daily values. For example, data that show strong spatial or temporal inconsistency are flagged. The monthly USHCN dataset was derived from the daily dataset in several steps. First, means for a given month were computed if no more than nine daily values were flagged or missing for that month. Second, the monthly dataset was subjected to further consistency checks that are qualitatively similar to the checks for the daily data. Third, the data were adjusted for time of observation, which has undergone significant change in the U.S. Fourth, a "change-point" detection algorithm was used to adjust the temperature for other inhomogeneities, such as change in station location, change in instrumentation, and change in nearby land use (e.g., urbanization).

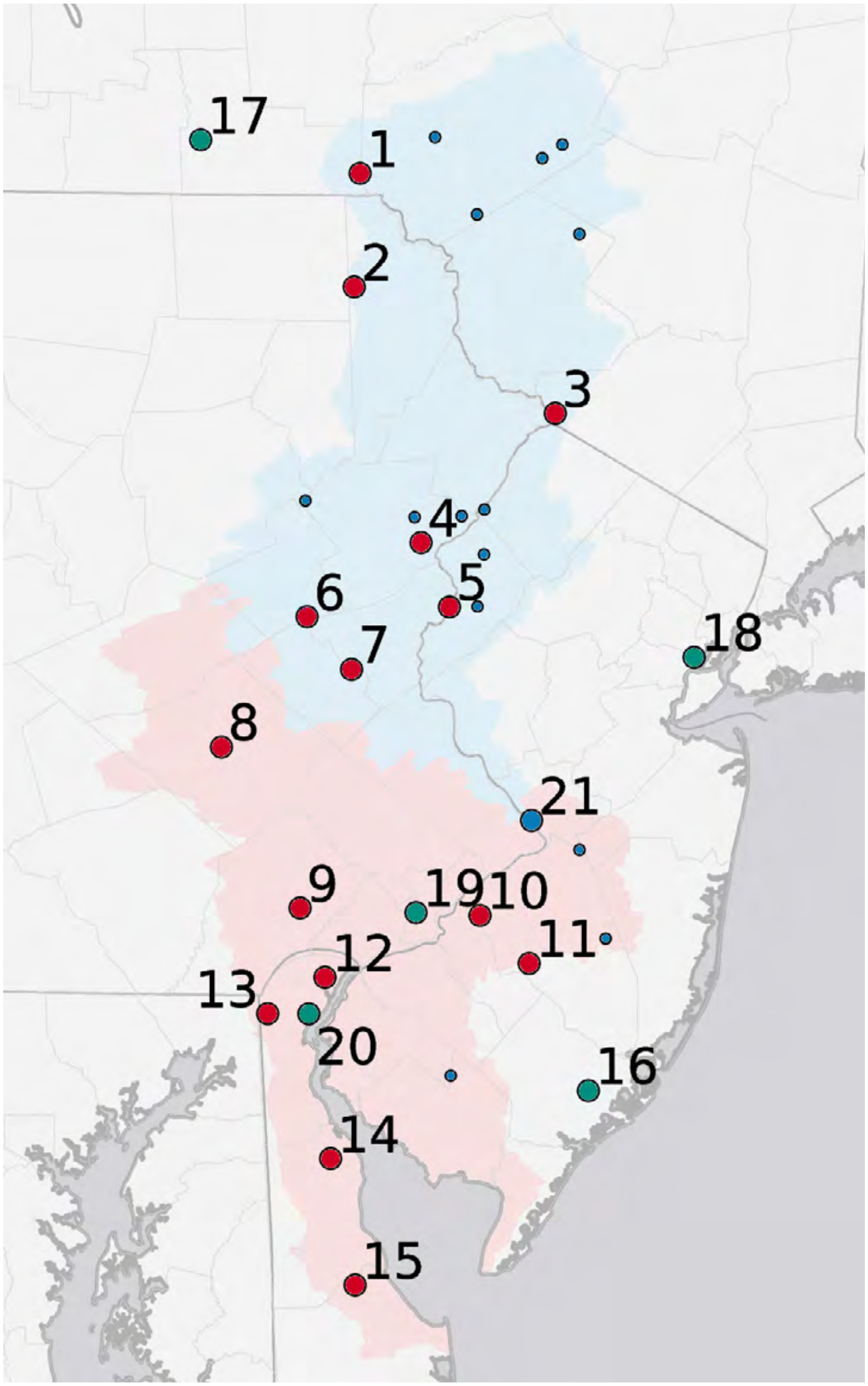


Figure 7.1.1 Location of meteorological and hydrological stations used in this analysis. Red dots (1–15) are the USHCN stations (section 7A); green dots (16–20) are the wind stations (7E); the blue dot (21) is the stream gauge at Trenton (7F).

The 15 USHCN stations located in or near the DRB were selected for analysis (Table 7.1.1). The analysis distinguished between the upper and lower portions of the watershed. The lower portion of the watershed is defined by those basins that deliver freshwater directly to tidal waters, which are located below Trenton, NJ. The upper portion of the watershed drains to the Delaware River above Trenton. There are 8 USHCN stations in the lower portion and 7 in the upper portion.

The period 1910–2015 was selected for analysis based on the monthly dataset because every station has a value during this time period (some data being estimated from an average of neighboring stations during the consistency check and homogenization procedures).

7.1.2 Past trends

Annual-mean temperature has increased significantly at the 95% confidence interval over the last 106 years (Fig 7.1.2-7.1.3, Table 7.1.2). Based on these trends, temperature has increased by roughly 1.0 to 1.2 °C over the last century. This rate is consistent with the predicted effect of greenhouse gases (Najjar et al. 2009). The estimated trend in annual mean temperature during the past 30 years is around three times greater than during the last century.

Since 1910, significant warming trends are also present in both portions of the watersheds for all seasons except for winter in the lower watershed (Fig 7.1.4, Table 7.1.2). In the recent 30-year period, both watersheds show significant fall temperature increases.

Substantial adjustments to the temperature data were necessary to account for changing observation times, station relocations, thermometer changes, and other causes of inhomogeneity (Fig 7.1.5). The effect of these adjustments is to increase the calculated temperature trend; adjustments increase the 1910–2015 temperature trend from from 0.015 to 0.099 °C/decade in the upper watershed and from 0.042 to 0.12 °C/decade in the lower watershed. Although these adjustments are large, they are necessary to account for the predominantly cooling effect of the thermometer and observation time changes. Studies of the U.S. temperature record have demonstrated that the adjustment algorithms are capable of significantly reducing errors and biases in data (Williams et al. 2012), and recent, high quality measurements of temperature are consistent with the adjusted data (Menne et al. 2010).

7.1.3 Future predictions

Future temperature changes in the DRB are strongly dependent on the amount of future global greenhouse gas (GHG) emissions. A variety of scenarios for future GHG emissions, or emissions scenarios, have been proposed. These can be broadly catagorized into high emissions scenarios that assume that emissions will continue at a pace similar to the present (the RCP 8.5 and A2 scenarios) and low emissions scenarios that assume significant global efforts to reduce emissions (the RCP 2.6, RCP 4.5 and B1 scenarios).

If GHG emissions remain high, the latest generation of global climate models (GCMs) project that some parts of the DRB will be 5 °C warmer at the end of the 21st century compared to the end of the 20th century (Walsh et al. 2014). On the other hand, if emissions are quickly and significantly reduced, the DRB is projected to be less than 2 °C warmer. The warming in the models is spread relatively evenly throughout the year, with the greatest warming in winter and a secondary peak in summer (Lynch et al. 2016). High-resolution regional climate models (RCMs) produce a similar seasonal pattern and, on average, predict greater winter warming in the northern region of the DRB and greater summer warming in the southern region (Rawlins et al. 2012). The historical climatology of temperature is relatively well-simulated by these RCMs, and all models agree that the future will be warmer, raising confidence in the model results (Rawlins et al. 2012).

7.1.4 Actions and needs

The cause of the substantial warming observed in the DRB requires further investigation. Though numerous studies have been conducted to determine the causes of long-term temperature trends at continental and global scales, there has only been one study specifically for the DRB (Najjar et al. 2009), which used GCMs from the 2001 Intergovernmental Panel on Climate Change report. Analysis of daily high and low temperatures may provide some insight as to the causes of long-term temperature change as these quantities respond differently to various types of radiative forcing, such as changes in greenhouse gases, aerosols, and cloudiness.

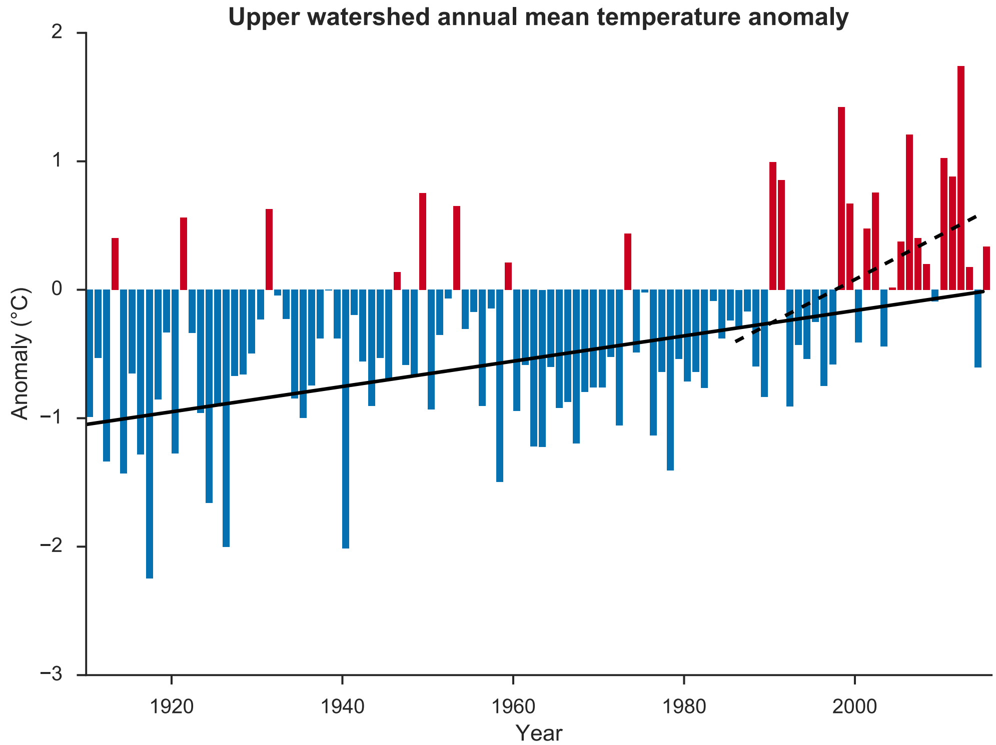
7.1.5 Summary

The DRB has warmed substantially over the past 106 years, and the rate of warming appears to be increasing. This change is qualitatively consistent with that expected from increases in greenhouse gases, but the large uncertainty in the temperature data combined with the limited attribution studies indicates that additional research is needed to better understand past temperature change. Future temperature change may be paradoxically more certain: not a single climate model projects cooling even under the low emissions scenario analyzed in Kreeger et al. (2010).

Table 7.1.1 USHCN stations used in the analysis. Numbers (first column) correspond to the numbers plotted on the map in figure 7.1.1. The start–end dates shown are defined as the first and last year for which precipitation data passed the quality-control procedures for precipitation extremes (See Section 4). Some stations have data before 1910, but are not listed as such because the present analysis begins in 1910. Stations above the horizontal line between Allentown and Reading are in the upper watershed, and stations below the line are in the lower watershed.

#	Name	State	ID number	Coordinates (dec. deg.)		Elev. m	Start–end
				Latitude	Longitude		
1	Deposit	NY	302060	42.0628	-75.4264	304.8	1963–2011
2	Pleasant Mt. 1 W	PA	367029	41.7394	-75.4464	548.6	1926–2014
3	Port Jervis	NY	306774	41.3800	-74.6847	143.3	1910–2014
4	Stroudsburg	PA	368596	41.0125	-75.1906	140.2	1912–2014
5	Belvidere BRG	NJ	280734	40.8292	-75.0836	80.2	1983–2014
6	Palmerton	PA	366689	40.8000	-75.6167	125.0	1918–1997
7	Allentown AP	PA	360106	40.6508	-75.4492	118.9	1948–2014
8	Reading 4 NNW	PA	367322	40.4269	-75.9319	109.7	1974–2007
9	West Chester 2 NW	PA	369464	39.9708	-75.6350	114.3	1911–2014
10	Moorestown	NJ	285728	39.9511	-74.9697	13.7	1911–2008
11	Indian Mills 2 W	NJ	284229	39.8144	-74.7883	30.5	1910–2014
12	Wilmington Porter Res.	DE	079605	39.7739	-75.5414	82.3	1942–2014
13	Newark Univ. Farm	DE	076410	39.6694	-75.7514	27.4	1942–1999
14	Dover	DE	072730	39.2583	-75.5167	9.1	1910–2011
15	Milford 2 SE	DE	075915	38.8983	-75.4250	10.7	1916–2001

A.



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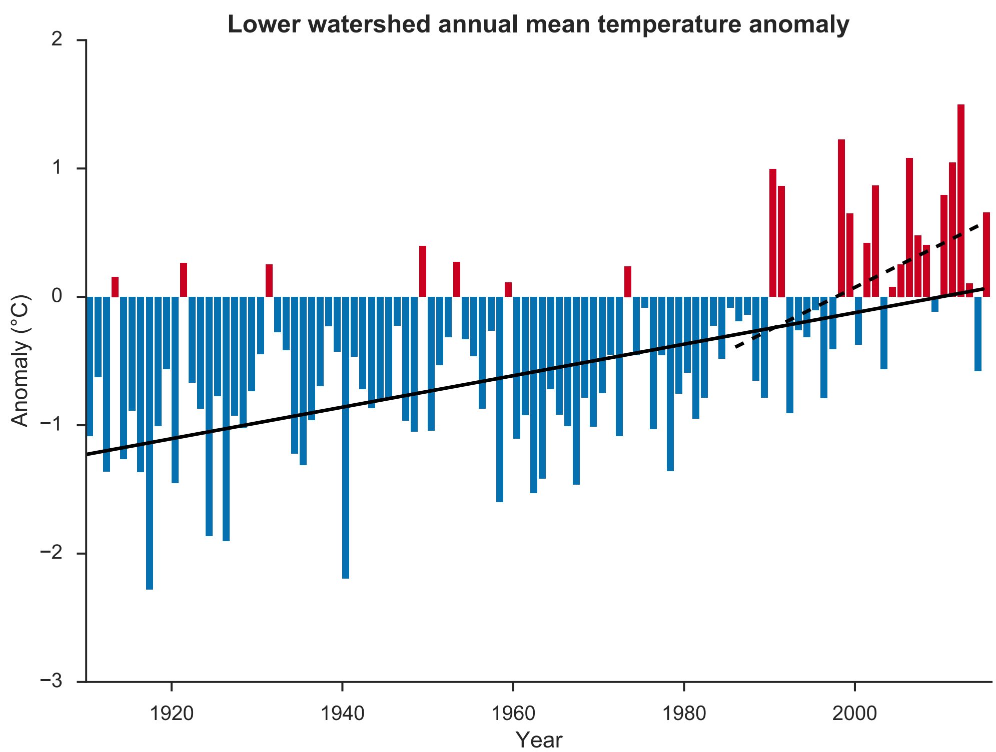

Figure 7.1.2 Anomalies (with respect to the 1981–2010 average) of annual-mean temperature for the upper (A) and lower (B) portion of the DRB. The solid and dashed lines are linear trends for the 1910–2015 and 1986–2015 periods, respectively.

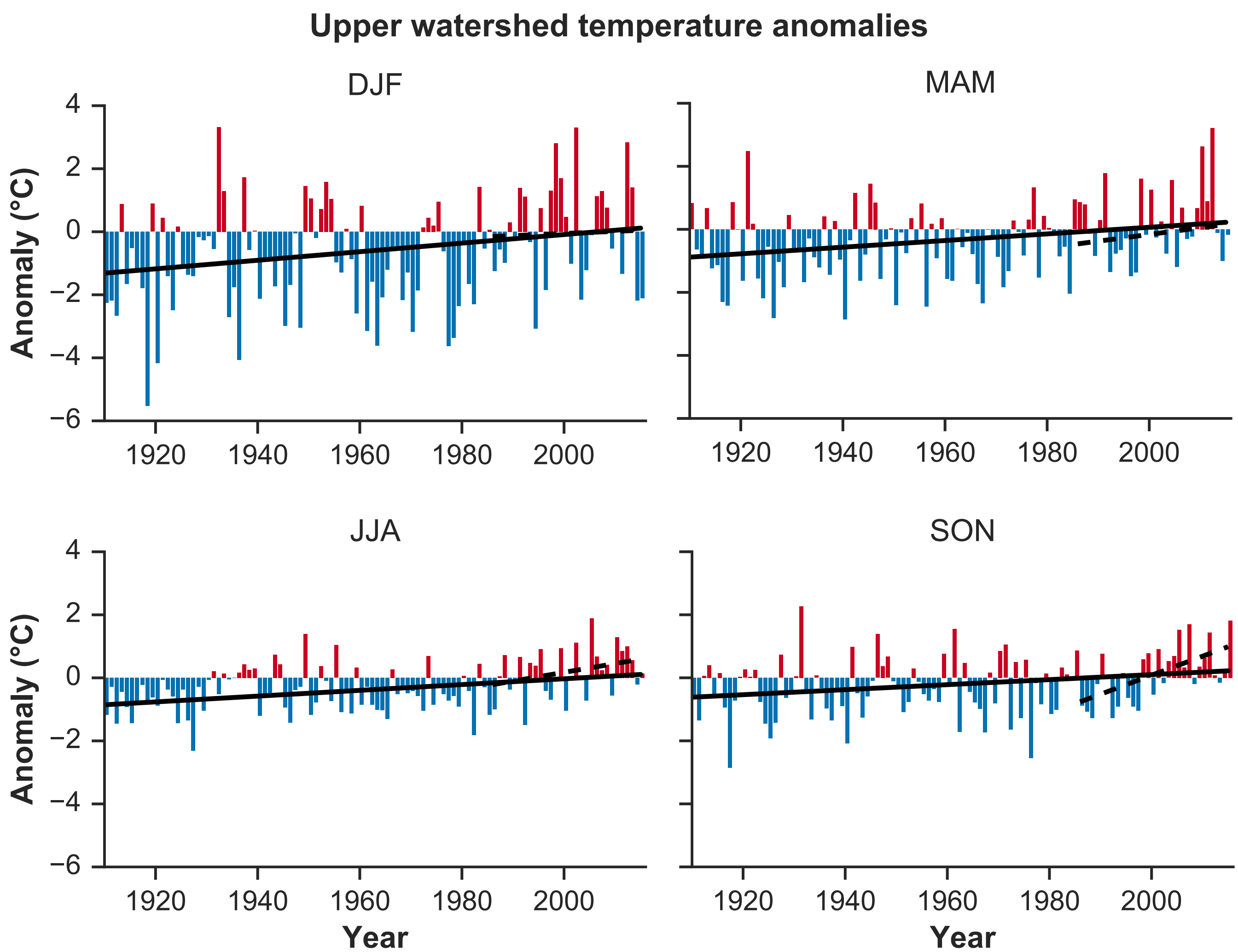

Figure 7.1.3 Anomalies (with respect to the 1981–2010 average) of seasonal-mean temperature for the upper portion of the DRB. The solid and dashed lines are linear trends for the 1910–2015 and 1986–2015 periods, respectively.

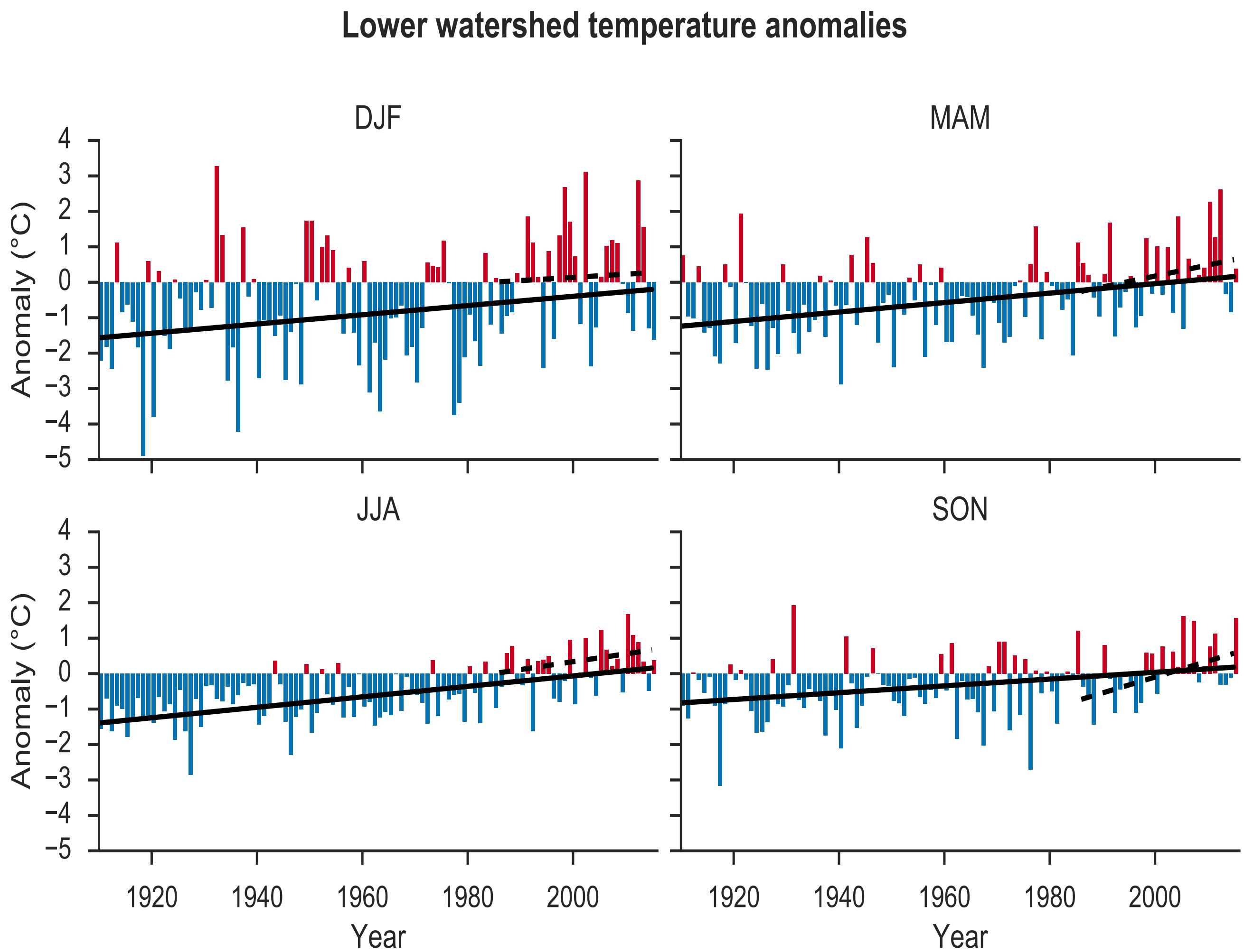

Figure 7.1.4 Anomalies (with respect to the 1981–2010 average) of seasonal-mean temperature for the lower portion of the DRB. The solid and dashed lines are linear trends for the 1910–2015 and 1986–2015 periods, respectively.

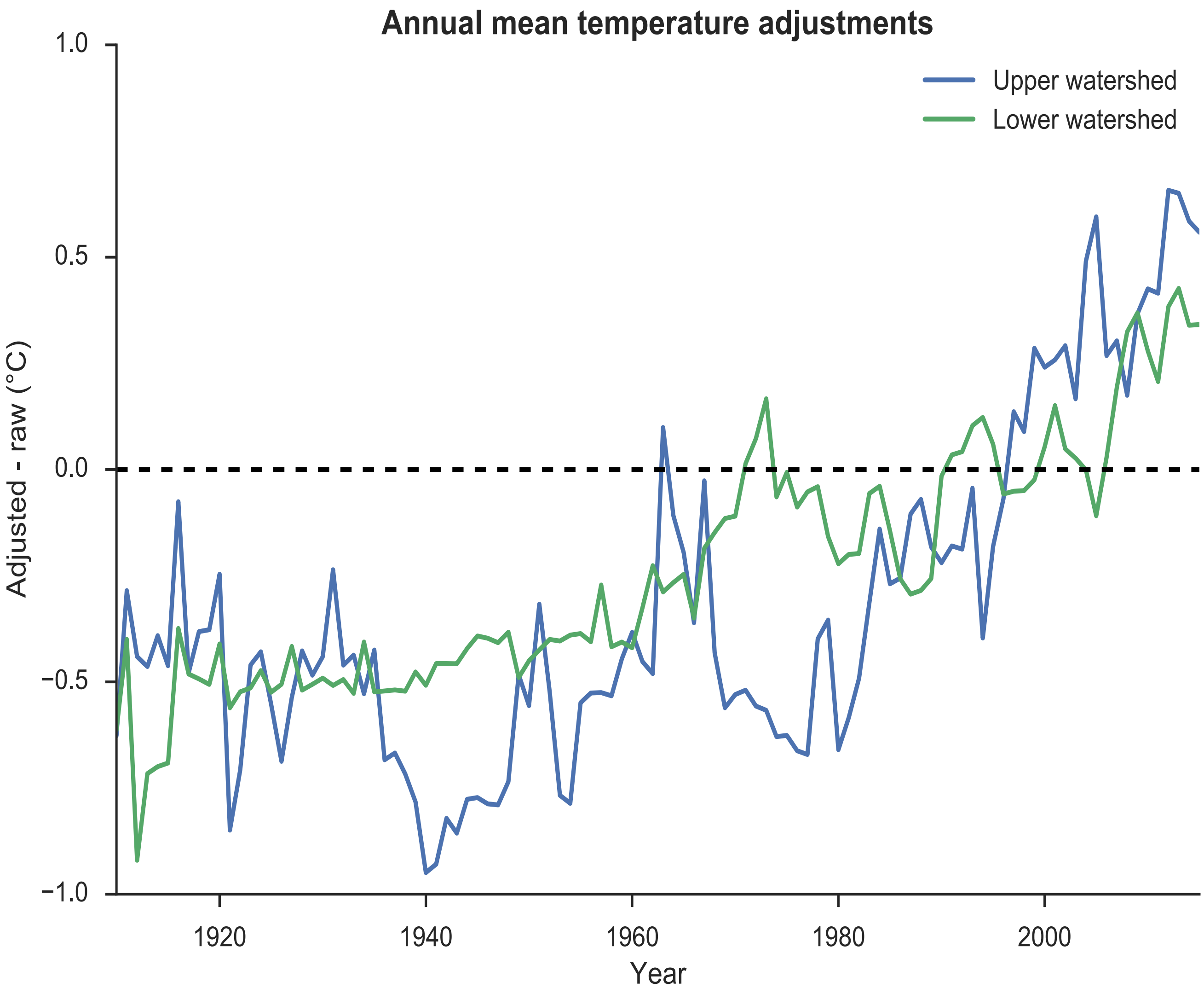

Figure 7.1.5 Impact of the adjustments to the monthly temperature data on the calculated annual mean temperatures. Shown is the difference between the time series of annual mean temperature calculated with the corrected data (as used in the text) and with the raw data for both subwatersheds.

Table 7.1.2 Linear trends of annual and seasonal mean temperature for the upper and lower portions of the DRB. p-values are in parentheses; trends significant at the 95% confidence level are bold.

	Seasonal Subset	Temperature Trend (°C/decade)	
		1910-2015	1986-2015
Upper Watershed	Annual	**0.099 (1.8×10^{-4})**	0.35 (0.088)
	DJF	**0.14 (0.036)**	0.068 (0.93)
	MAM	**0.11 (1.9×10^{-3})**	0.21 (0.28)
	JJA	**0.092 (2.0×10^{-4})**	0.28 (0.15)
	SON	**0.08 (0.011)**	**0.60 (4.1×10^{-3})**
Lower Watershed	Annual	**0.12 ($<10^{-4}$)**	0.33 (0.075)
	DJF	0.13 (0.055)	0.090 (0.93)
	MAM	**0.13 ($<10^{-4}$)**	0.31 (0.058)
	JJA	**0.15 ($<10^{-4}$)**	0.22 (0.22)
	SON	**0.096 (3.7×10^{-4})**	**0.45 (0.014)**

7.2 Precipitation

7.2.1 Description of Indicator

As with temperature, monthly precipitation totals were acquired from the USHCN version 2.5 dataset. The same stations were used, and the USHCN screening procedure was similar to the procedure for temperature except there is no time-of-observation correction.

7.2.2 Past trends

Annual precipitation totals have not increased with 95% confidence in either portion of the watershed (Fig 7.2.1-7.2.2, Table 7.2.1). Estimated trends in annual total precipitation over the most recent 30 years are about three times larger but are also not statistically significant. Seasonally (Figs 7.2.3-7.2.4, Table 7.3), fall precipitation totals have increased significantly in both watershed portions over the last 106 years.

7.2.3 Future predictions

There is a strong model consensus towards increased winter precipitation in the northern half of North America, including all of the DRB, in the future (Walsh et al. 2014; Lynch et al. 2016; Rawlins et al. 2012). A performance-weighted average of regional climate model simulations under a high emissions scenario yields a 10-14% increase in winter precipitation throughout the DRB by 2041–2070 (Rawlins et al. 2012). Most studies also show that increased spring precipitation is likely in the DRB, while changes in summer and fall precipitation are uncertain.

7.2.4 Actions and needs

The understanding of long-term changes in precipitation is poor. Observed precipitation trends in the DRB do not match model predictions of the effects of greenhouse gases on regional precipitation totals. Globally, most precipitation datasets show an increasing trend in mean precipitation during the last century, which is consistent with the expected effect of increasing greenhouse gases (Hartmann et al. 2013). However, observations vary widely between datasets, and the overall confidence in the trends is low (Hartmann et al. 2013). Finally, changes in extreme events should be studied, since model simulations of changes in extreme events show a stronger signal of climate change (Section 7.3).

7.2.5 Summary

There is some evidence that precipitation has increased in the DRB, particularly during the fall. Precipitation is projected to increase in the future, mainly during winter and spring. The projected precipitation changes are well within natural interannual variations (Najjar et al. 2009), which is possibly why the greenhouse gas signal has not been detected in the observations.

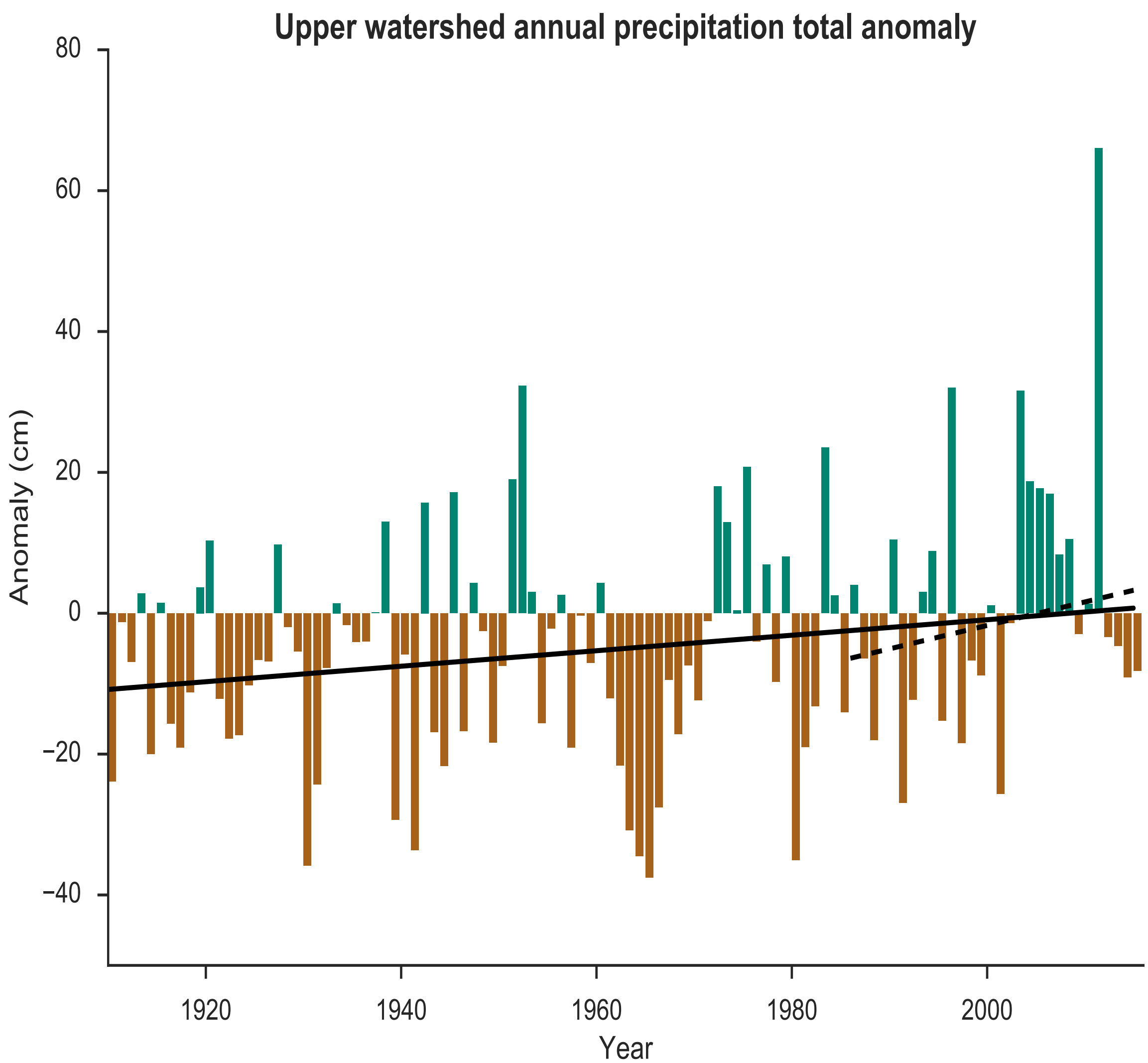

Figure 7.2.1 Anomalies (with respect to the 1981–2010 average) of annual precipitation totals for the upper portion of the DRB. The solid and dashed lines are linear trends for the 1910–2015 and 1986–2015 periods, respectively.

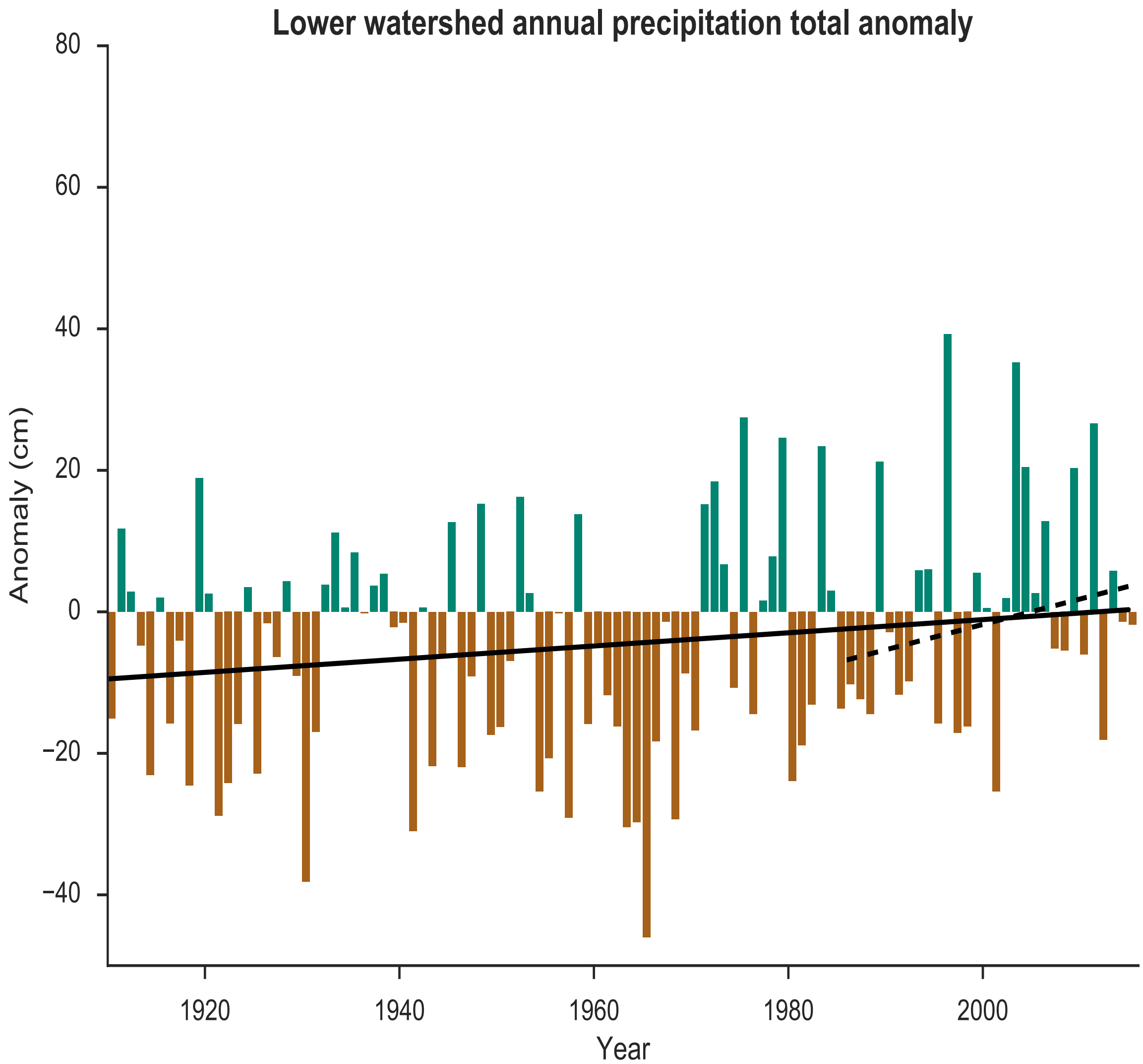

Figure 7.2.2 Anomalies (with respect to the 1981–2010 average) of annual precipitation totals for the lower portion of the DRB. The solid and dashed lines are linear trends for the 1910–2015 and 1986–2015 periods, respectively.

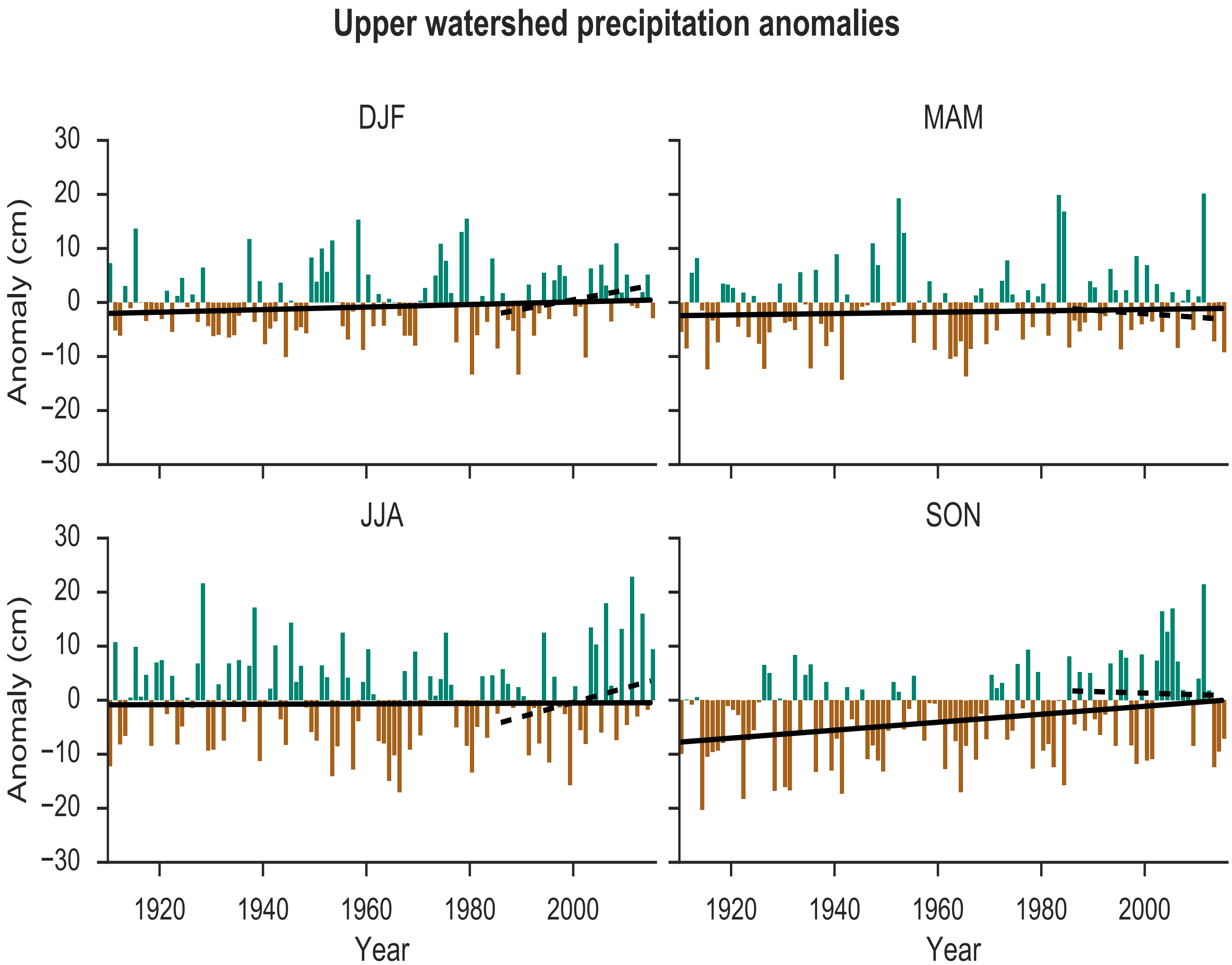

Figure 7.2.3 Anomalies (with respect to the 1981–2010 average) of seasonal precipitation totals for the upper portion of the DRB. The solid and dashed lines are linear trends for the 1910–2015 and 1986–2015 periods, respectively.

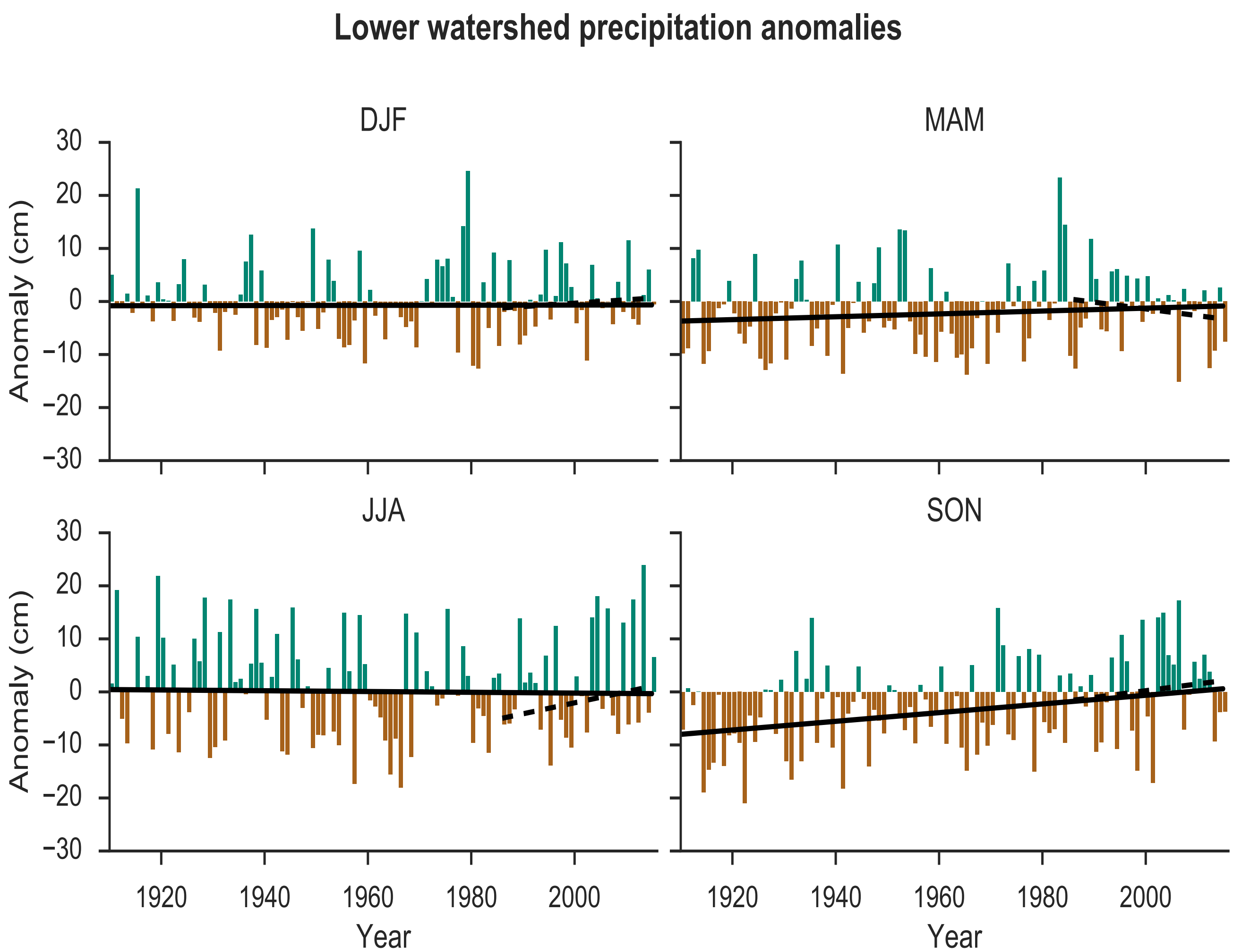

Figure 7.2.4 Anomalies (with respect to the 1981–2010 average) of seasonal precipitation totals for the lower portion of the DRB. The solid and dashed lines are linear trends for the 1910–2015 and 1986–2015 periods, respectively.

Table 7.2.1 Linear trends of annual and seasonal precipitation totals for the upper and lower portions of the DRB. p-values are in parentheses; trends significant at the 95% confidence level are bold.

	Seasonal Subset	Precipitation Trend (cm/decade)	
		1910-2015	1986-2015
Upper Watershed	Annual	1.1 (0.084)	3.3 (0.28)
	DJF	0.24 (0.14)	1.8 (0.063)
	MAM	0.13 (0.71)	-0.65 (0.64)
	JJA	0.037 (0.97)	2.7 (0.053)
	SON	**0.74 (0.032)**	-0.29 (0.96)
Lower Watershed	Annual	0.93 (0.11)	3.6 (0.32)
	DJF	0.015 (0.84)	0.63 (0.78)
	MAM	0.27 (0.43)	-1.3 (0.20)
	JJA	-0.073 (0.91)	2.1 (0.16)
	SON	**0.82 (1.2×10^{-3})**	1.3 (0.56)

7.3 Extremes: Air Temperature and Precipitation

7.3.1 Description of indicator

Trends in five extreme event indices were calculated: (1) T90, the number of days per year with high temperatures above 90 °F (32.2 °C); (2) FD, the number of frost days per year (days with low temperatures below 32 °C (0 °C); (3) CDD, the maximum number of consecutive dry days per year; (4) RX5day, the annual maximum five-day precipitation total in centimeters; (5) R45, the number of days per year with heavy (> 4.5 cm) precipitation.

The USHCN daily dataset was used for this analysis. Unlike the monthly data, the daily data are not adjusted for changes in station location, instrumentation, or time of observation, which may result in significant biases and artificial trends, particularly in the temperature data.

Temperature and precipitation data that were given any quality control failure flags in the dataset were removed. For precipitation data, a day was deemed dry if the reported precipitation total was less than 1 mm. Missing days were assumed to be wet for the CDD metric and dry for the RX5day metric.

7.3.2 Past trends

Many of the trends in the five extreme events indices are not statistically significant, with the notable exception of the days per year of heavy precipitation (R45) which shows an upward trend of 0.17-0.19 days per decade or slightly less than 2 days per century in both watersheds (Figs 7.3.1-7.3.2, Table 7.3.1). This may appear to be a small change but is, in fact, substantial, because there are so few days of heavy precipitation. Compared to the average for the 1981-2010 reference period (about 3 days per year), the increase is over 50%.

Both watersheds show decreases in the number of freezing days over the last century, although neither watershed reaches the bar of statistical significance. A trend towards fewer freezing days was found throughout the Northeast U.S. by Brown et al. (2010). Trends in the number of days above 90 °F are also positive but insignificant in both subwatersheds.

7.3.3 Future predictions

Both extreme wet and extreme dry events are expected to become more common by the end of the 21st century (Kreeger et al. 2010; Walsh et al. 2014; Wuebbles et al. 2014; Janssen et al. 2014), with larger changes in scenarios of high GHG emissions. By the middle of the 21st century, climate models also project a large increase in the number of days per year above 90 °C in the Northeast U.S., and a decrease in the number of days below freezing in the DRB, even under low emissions scenarios (Horton et al. 2014; Williamson et al. 2016).

7.3.4 Actions and needs

A more thorough analysis and literature review is needed for past trends in extremes in the DRB. A central issue is the homogenization and correction for non-climatic trends in the daily temperature data. Other studies, with different treatments of the data and different metrics (DeGaetano and Allen 2002; Brown et al. 2010), show some substantial differences with our analysis, and these need to be resolved. Recently developed datasets that apply adjustments at the daily level may provide a better picture of changing temperature extremes. In addition, due to the size and variable topography and land use of the DRB,

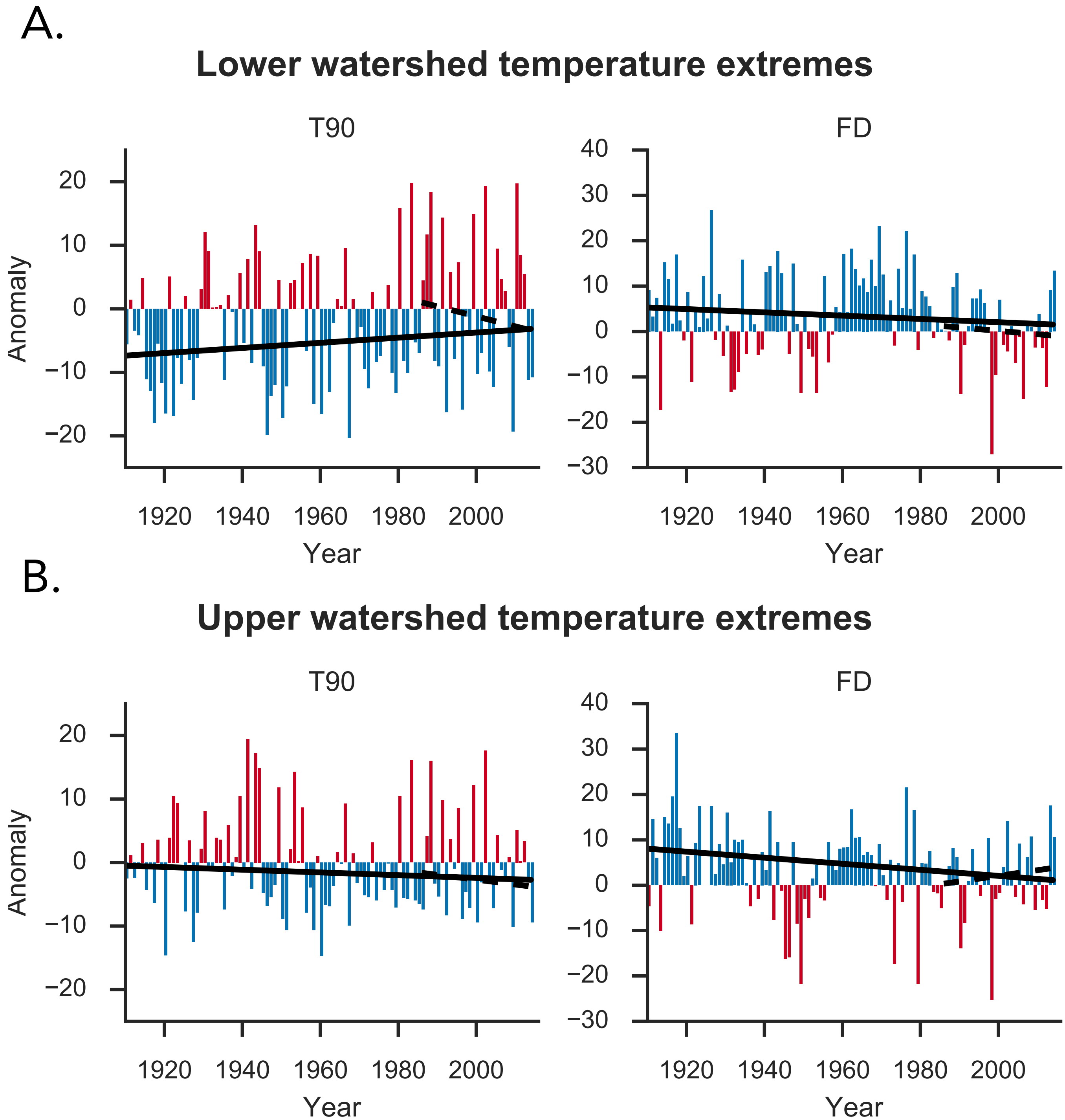

Figure 7.3.1 Time series of the anomalies (with respect to the 1981–2010 average) of the number of days per year with low temperature below 32 °F (0 °C) and high temperature above 90 °F (32.2 °C) in the A) upper and B) lower portions of the watershed. The solid and dashed lines are linear trends for the 1910–2014 and 1986–2014 periods, respectively.

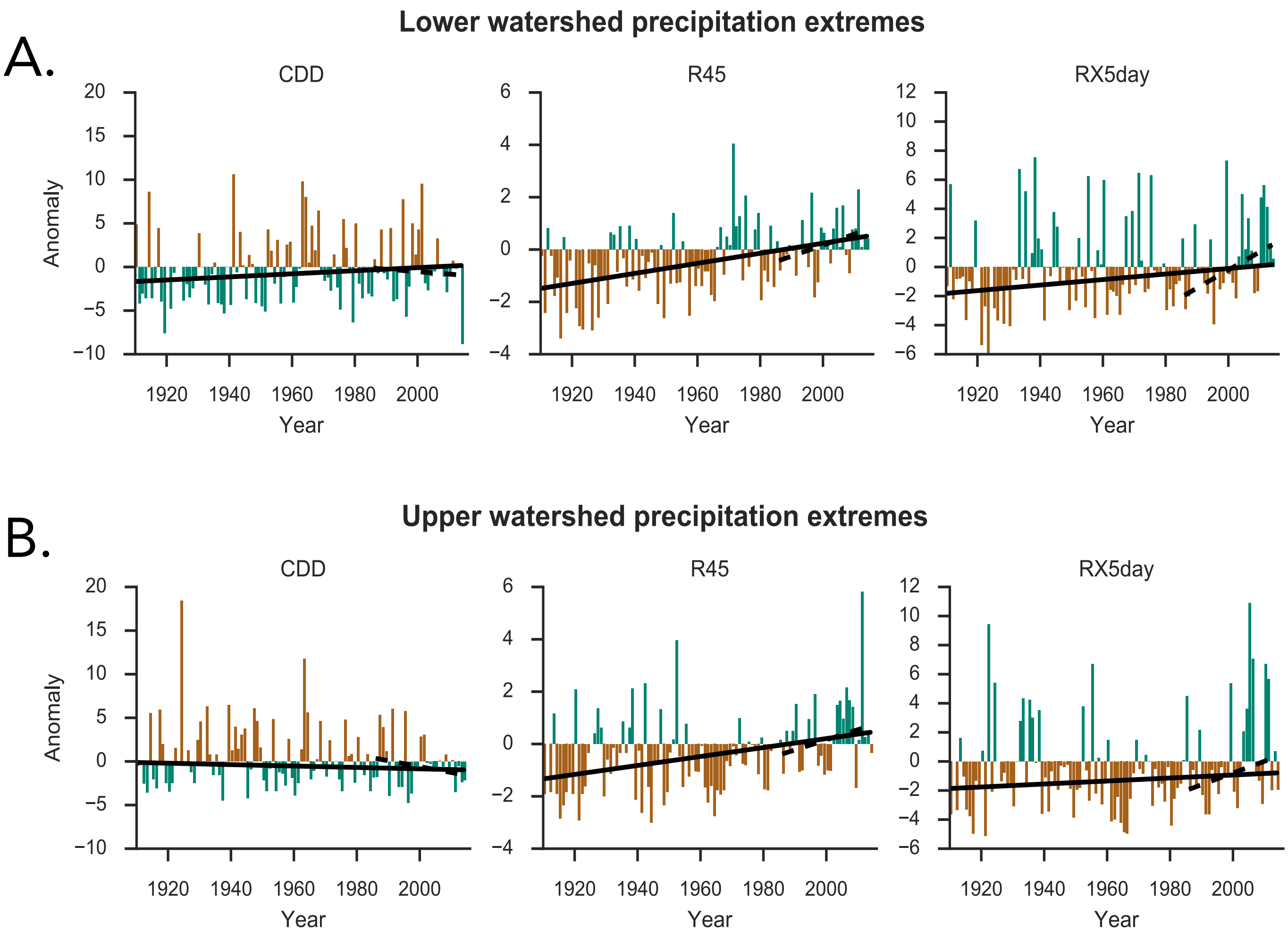

Figure 7.3.2 Time series of the anomalies (with respect to the 1981–2010 average) of the precipitation extreme metrics in the A) upper and B) lower portions of the watershed. The solid and dashed lines are linear trends for the 1910–2014 and 1986–2014 periods, respectively.

changes in temperature and precipitation extremes may have high spatial variability. Future work could analyze trends at the scale of individual stations and apply high-resolution regional climate models or other downscaling techniques.

7.3.5 Summary

The intensity and frequency of extreme temperature and precipitation events are difficult to examine directly and even harder to predict. Despite increased overall temperatures in the DRB over the past century, no significant increase in high temperature extreme events was detected in this analysis. On the other hand, heavy precipitation events increased in frequency in both the Upper and Lower Basin. Most climate scientists predict increasing extreme events in the future, but there is still a lot of uncertainty in this facet of climate science.

Table 7.3.1 Linear trends of extreme event indices for the upper and lower portions of the DRB. p-values are in parentheses; trends significant at the 95% confidence level are bold.

	Metric	1981-2010 Average	Trend (per decade)	
			1910-2015	1986-2015
Upper Watershed	# days per year above 90 °F	14	-0.21 (0.28)	-1.4 (0.28)
	# days per year below 32 °F	130	**-0.67 (0.043)**	1.1 (0.56)
	Annual max # consecutive dry days	15	-0.081 (0.35)	-0.96 (0.28)
	# days/year with precip >4.5 cm	2.8	**0.17 (5×10^{-4})**	0.3 (0.32)
	Annual max 5-day precip. total	11	0.1 (0.4)	0.78 (0.28)
Lower Watershed	# days per year above 90 °F	26	0.4 (0.12)	-1.4 (0.77)
	# days per year below 32 °F	93	-0.36 (0.42)	-1.3 (0.50)
	Annual max # consecutive dry days	17	0.18 (0.13)	-0.17(0.68)
	# days/year with precip >4.5 cm	3.3	**0.19 ($<10^{-4}$)**	0.38 (0.087)
	Annual max 5-day precip. total	11	0.19 (0.078)	1 (0.18)

7.4 Snow Cover

7.4.1 Description

Snow cover data was obtained from the NOAA Climate Data Record of Northern Hemisphere Snow Cover Extent, Version 1 (https://data.noaa.gov/dataset/noaa-climate-data-record-cdr-of-northern-hemisphere-nh-snow-cover-extent-sce-version-1). This dataset provides gridded, satellite-derived observations of snow cover at weekly intervals. Snow cover is provided as a binary variable, indicating either the presence or absence of snow; no information about snow depth is available. For this analysis, three grid cells within the DRB were selected. Within a given snow year (year ending in July), the percent of weeks where at least one of the three cells had snow cover was calculated.

7.4.2 Past trends

Figure 7.4.1 shows that snow cover in the DRB has varied dramatically, with some years having several months of snow cover and other years having nearly zero snow cover. The linear trend during 1967–2016 is essentially zero. The trend for winters starting in 1986 and ending in 2016 is significantly positive at a rate of 3.7% per decade (p=0.018).

Climate oscillations have a large role in determining winter snow cover. Figure 7.4.1 also shows the winter mean North Atlantic Oscillation (NAO) index, acquired from the Climate Prediction Center. Snow cover percentage and mean NAO index are significantly negatively correlated (correlation coefficient =-0.45), and the fluctuations in the NAO index clearly align with anomalous snow cover periods such as the low snow cover during the late 1980s and early 90s and the high snow cover during the late 1960s and 70s. Since 2000, the NAO index has primarily been neutral or positive, yet snow cover has mostly been unusually high.

7.4.3 Future predictions

In the upper Delaware River watershed, snowpack during December through March is projected to be approximately half of the present-day snowpack by the mid-21st century under several different GHG emissions scenarios (Matonse et al. 2011). Global climate model simulations suggest that average snowfall in the mid-Atlantic region is not yet statistically different from early 20th century snowfall, but a detectable difference will emerge within the next two decades (Krasting et al. 2013).

7.4.4 Actions and needs

Snowfall depends on many factors in addition to temperature, such as the status of the NAO, El Niño-Southern Oscillation (ENSO), and other climate oscillations (Seager et al. 2010);

Therefore, the understanding of how climate affects snowfall would benefit from a more robust analysis of how local and regional weather events are affected by changing climate and associated weather patterns. Research would also benefit from additional datasets of observed snow-related variables, including measurements of snow depth.

7.4.5 Summary

Snowfall is highly variable from year to year, influenced by many factors that govern upper air movements, storm intensity, and temperature. It is just as related to short-term weather patterns as it is to long-term climate patterns. It is plausible that snowfall could actually increase in the future if deeper winter storms more routinely entrain cold northern air that would normally stay north of the DRB. On the other hand, warmer winters are predicted to cause a decrease in the depth, range, and duration of the snowpack. Therefore, it may snow just as much in the future but it may not stick around for as long as in the past, leading to faster freshwater runoff in streams and rivers.

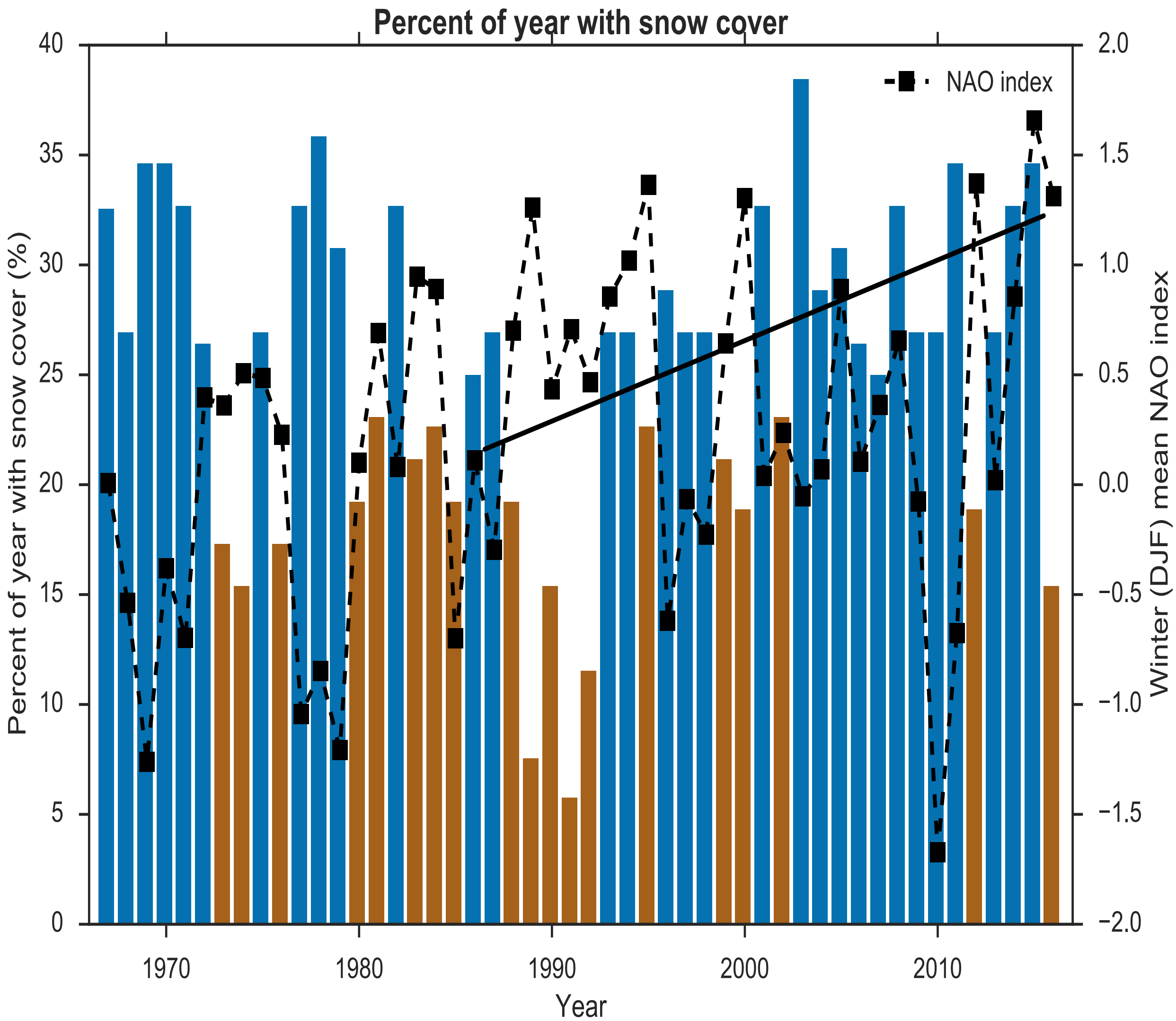

Figure 7.4.1 Time series of percent of the year with snow cover in the Delaware River Basin. Blue bars indicate a year with a greater snow cover percentage than the 1981–2010 mean of 24%; brown bars indicate a year with less snow cover. The solid line is the linear trend for the 1986–2016 period; the trend for the full time series is near zero. The dashed line is the winter mean NAO index.

7.5 Wind speed

7.5.1 Description of Indicator

Wind speed data were acquired from the National Climatic Data Center (NCDC) for five stations in the region (see Fig 7.1.1): Atlantic City, NJ (1973-2015); Binghamton, NY (1973-2015); Newark, NJ (1973-2015); Philadelphia, PA (1965-2015); and Wilmington, DE (1973-2009). The data processing and methods of analysis are similar to those of Vautard et al. (2010). Hourly averages at four times per day were acquired (00, 06, 12, and 18 UTC). Values flagged as suspect or erroneous by the NCDC were removed. The data were filtered using the came criteria as for the daily data: if for any month in a season or year contained more than five measurements missing from any of the four hours, the entire season or year from that station was considered missing.

The analysis was restricted to the period after 1965 because of a change in the reporting of low wind speeds in the early 1960s (DeGaetano and Allen 2002). A change in instrumentation occurred in 1995, when the stations became part of the Automated Surface Observing System (ASOS) of the National Weather Service. According to McKee et al. (1996), such a change resulted in low winds reported lower and high winds reported higher; calm wind reports nearly doubled. To avoid including the effects of this instrumentation switch, trends were calculated separately for the 1965-1994 and 1996–2015 periods.

Anomalies for wind speed were calculated with respect to the 1974–1992 average, during which most stations have data and were using consistent instrumentation, and averaged over the five stations. Anomalies were calculated for both the annual and seasonal mean wind speeds and for the annual and seasonal percent of hours with wind speeds exceeding 2, 5, and 7 $m \cdot s^{-1}$.

7.5.2 Past trends

Annual mean wind speed has declined by about 0.8 $m \cdot s^{-1}$ over the last 51 years (Fig 7.5.1). This trend is remarkably large compared to the 1974–1992 mean value of 4.3 $m \cdot s^{-1}$. The trend is relatively uniform across the seasons (Table 7.5.1, Fig 7.5.2), with the exception of a weaker summer trend before 1995. However, summer trends may be particularly affected by instrumentation and reporting standards, since calm winds are most common in summer.

The wind speed declines are consistently negative across the wind speed distribution (Figs 7.5.3 and 7.5.4). The trend in wind speeds exceeding 5 $m \cdot s^{-1}$ is the most negative trend both before and after 1995. Most of the plotted trend lines are statistically significant, including all of the annual trends. After 1995, all seasonal trends are significant except for the winter trends at all thresholds and the autumn trend in winds above 7 $m \cdot s^{-1}$. Before 1995, summer trends at all thresholds are not significant, along with autumn winds above 7 $m \cdot s^{-1}$ and spring and winter winds above 2 $m \cdot s^{-1}$.

These results are consistent with studies showing declining near-surface wind speeds in the tropical and mid-latitude regions of both the Northern and Southern Hemispheres over at least the last 30 years (Pryor et al. 2009; Vautard et al. 2010; McVicar et al. 2012). These declines are not matched by wind declines aloft, suggesting that surface roughness changes, perhaps resulting from land-use change, were responsible for the surface wind declines (Vautard et al. 2010). In fact, winds above the surface (at a pressure of 850 mb) have increased over much of North America, including the northeastern U.S. (Vautard et al. 2010).

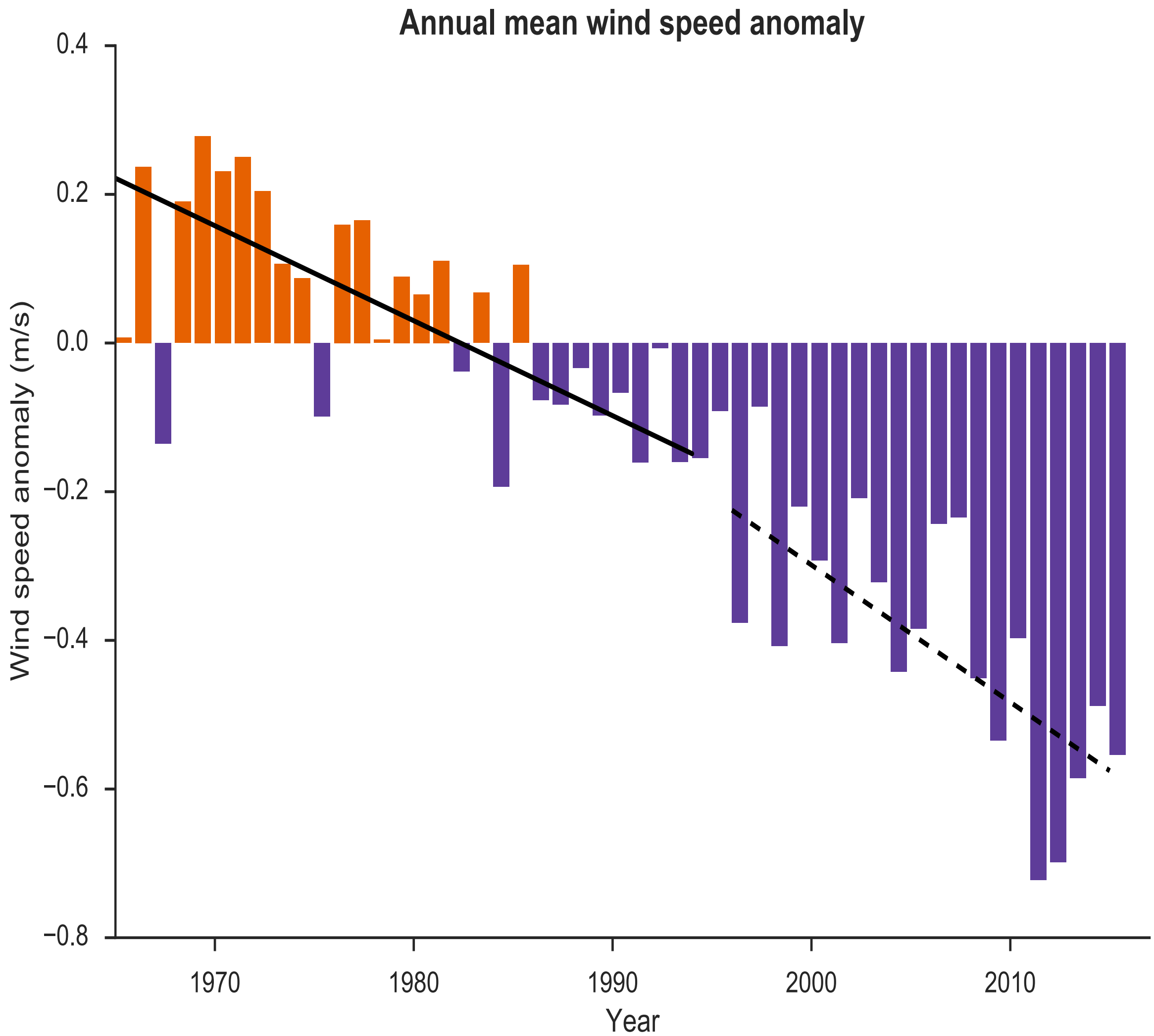

Figure 7.5.1 Time series of annual mean wind speed anomalies (with respect to 1974–1992 mean) averaged over the five wind stations. The solid line denotes the 1965–1994 trend, and the dashed line denotes the 1996–2015 trend.

Table 7.5.1 Mean and linear trends of annual and seasonal mean wind speed averaged over the five wind speed stations (see text).

Seasonal Subset	Wind Speed	
	Mean (m/s)	Trend (m/s/decade)
Annual	4.3	-0.18
DJF	4.6	-0.20
MAM	4.7	-0.22
JJA	3.8	-0.21
SON	4.0	-0.16

7.5.3 Future predictions

Future predictions of wind speed have not been analyzed in the DRB specifically. Across the United States, regional climate models have different projections about the sign and magnitude of future wind speed changes (Pryor and Barthelmie 2011). Since land-use and management changes are thought to have driven past changes, future winds may also depend more on land-use and management than on climate.

7.5.4 Actions and needs

Wind speeds are decreasing, which could have diverse effects on weather, agriculture, and other topics important to people and the environment. More study is needed to examine, for example, whether weaker winds might reduce evapotranspiration, promote slower-moving thunderstorms and more persistent fog, thereby affecting the water budget and growing conditions for plants and animals. Future work should also investigate whether wind direction has been changing or is predicted to change, and what effects changes in both wind speed and direction could have on the DRB.

7.5.5 Summary

Wind speeds have been declining across the Delaware River Basin. The cause of the wind speed decline is not known, but it may result from changes in surface properties, such as land use. Augmenting the current wind speed analysis with data on land use change and a regional climate model should be helpful in determining the cause of wind speed change in the DRB.

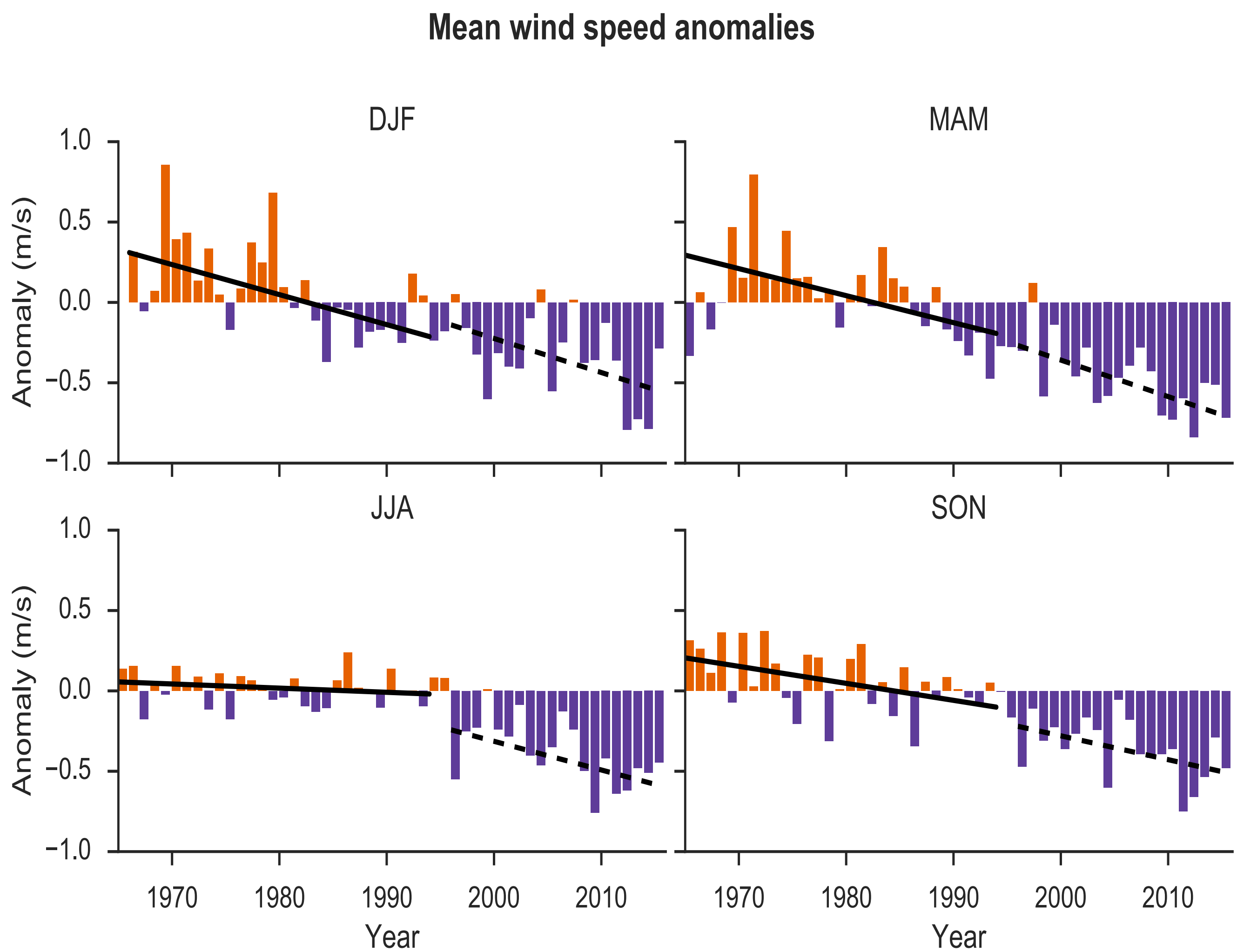

Figure 7.5.2 Time series of wind speed anomalies (with respect to 1974–1992 mean) averaged over the five wind stations. The solid lines denote the 1965–1994 trends, and the dashed lines denote the 1996–2015 trends.

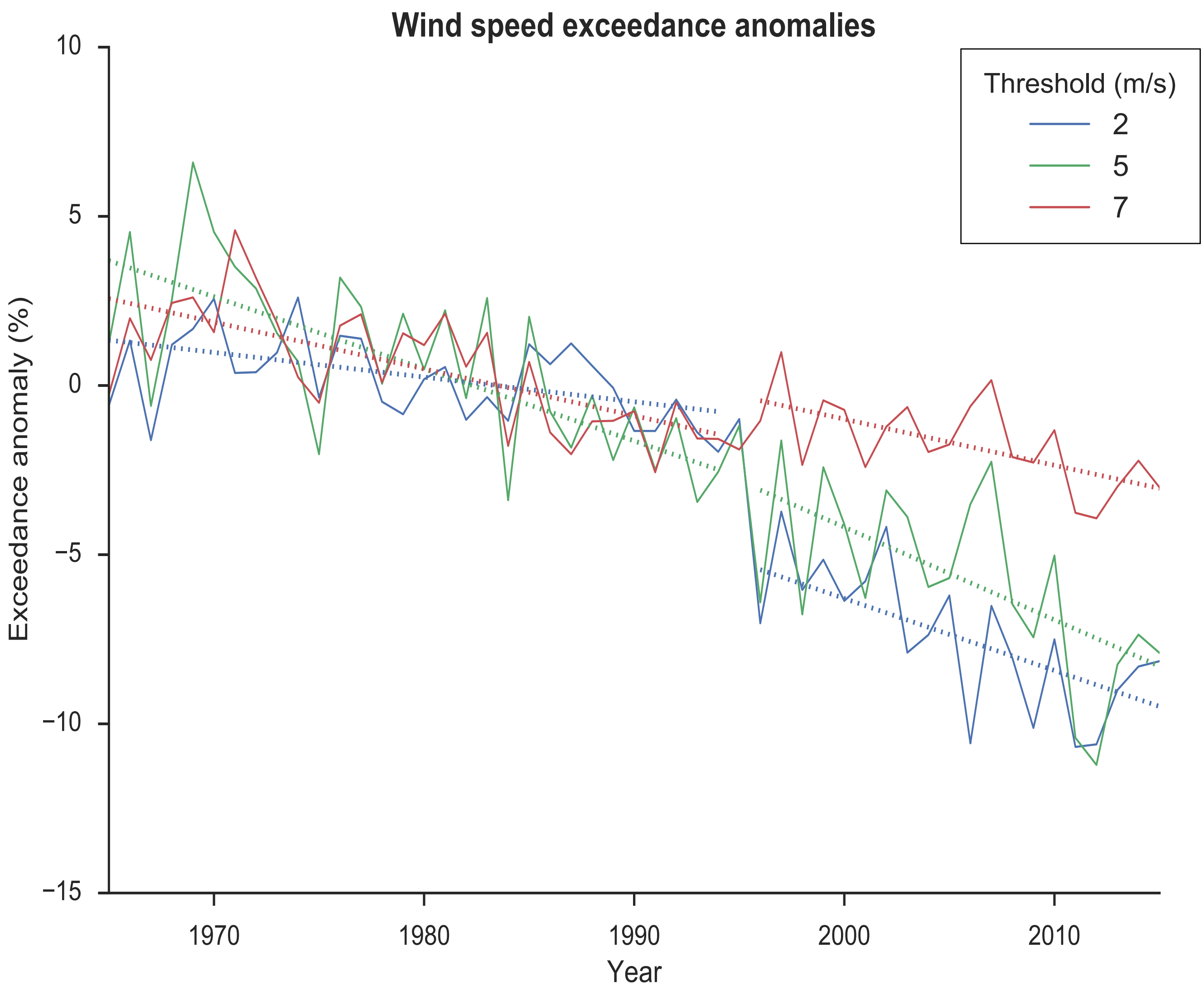

Figure 7.5.3 Time series of the wind speed exceedance anomalies (with respect to the 1974–1992 mean) averaged over the five wind stations. The dashed lines denote the 1965–1994 trends and 1996–2015 trends.

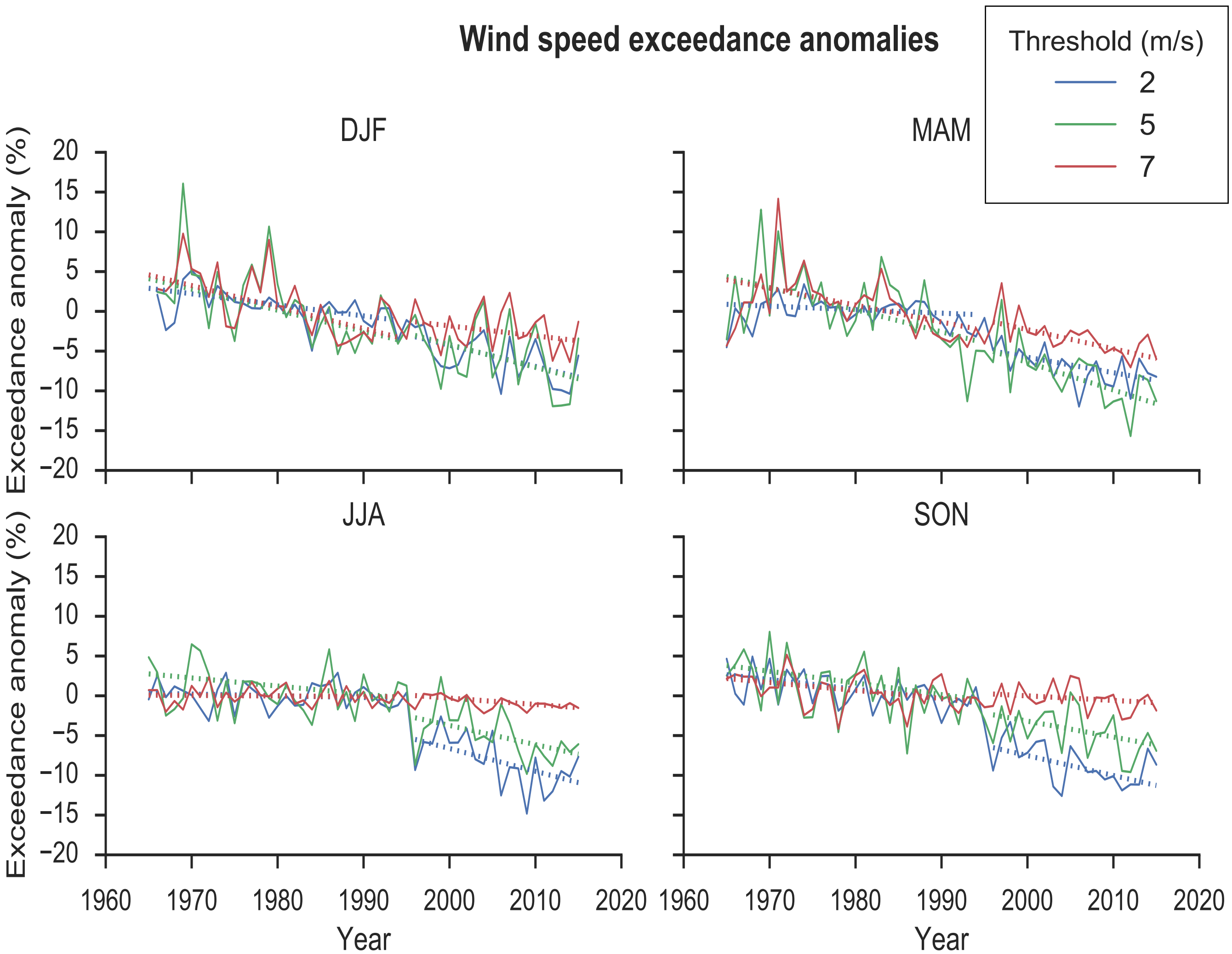

Figure 7.5.4 Time series of the wind speed exceedance anomalies (with respect to the 1974–1992 mean) averaged over the five wind stations. The dashed lines denote the 1965–1994 trends and 1996–2015 trends.

7.6 Streamflow

7.6.1 Description of Indicator

Daily streamflow data were obtained from the United States Geological Survey. The analysis primarily focuses on the streamflow measured in the Delaware River at Trenton, NJ. However, since the flow at Trenton is highly regulated, a set of data from smaller, unregulated, tributaries was also included. The tributaries were selected from those that are noted in the 2009 version of the Hydro-Climatic Data Network (HCDN) dataset (Slack et al. 1993) as having a complete record of acceptable data and that include complete daily data during 1981 to 2010. Sites listed in the HCDN dataset have passed a number of checks to ensure that the flow data from the sites are not affected by human activity such as dams, impervious surfaces, and water withdrawal and discharge. Information about the 10 selected gauges is provided in Table 7.6.1. The gauges are concentrated in the northern portion of the DRB; only three are south of Trenton. Data from the tributaries were analyzed during years 1958 to 2014 when data were available at every gauge. Like other daily data, flow data from both the Delaware River and the tributaries were filtered to remove years and seasons with more than 5 days of data missing in any month.

To homogenize the tributary river data, standardized anomalies were calculated for each gauge. The standardized anomaly Q' was calculated as

$$Q' = \frac{Q - \overline{Q}}{Q_\sigma}$$

where Q is the time series of annual or seasonal mean streamflow, □Q is the 1981–2010 mean of the time series, and Q_σ is the 1981–2010 standard deviation of the time series.

7.6.2 Past trends

Streamflow at Trenton, NJ has varied substantially over the past century, with many years departing from the long-term mean by more than 50% (Figs 7.6.1-7.6.2). Aside from a large increase in summer streamflow over the last 30 years, no trend in streamflow is statistically significant. Despite lack of significance, the estimated values of the trends over the last century are generally consistent with trends over the last 30 years, with positive trends in winter, summer, and fall and negative trends in spring.

Table 7.6.1 Metadata for the tributary flow gages.

ID	Name
01413500	East Br Delaware R at Margaretville, NY
01414500	Mill Brook near Dunraven, NY
01415000	Tremper Kill near Andes, NY
01423000	West Branch Delaware River at Walton, NY
01435000	Neversink River near Claryville, NY
01439500	Bush Kill at Shoemakers, PA
01440000	Flat Brook near Flatbrookville, NJ
01440400	Brodhead Creek near Analomink, PA
01466500	McDonalds Branch in Lebanon State Forest, NJ
01484100	Beaverdam Branch at Houston, DE

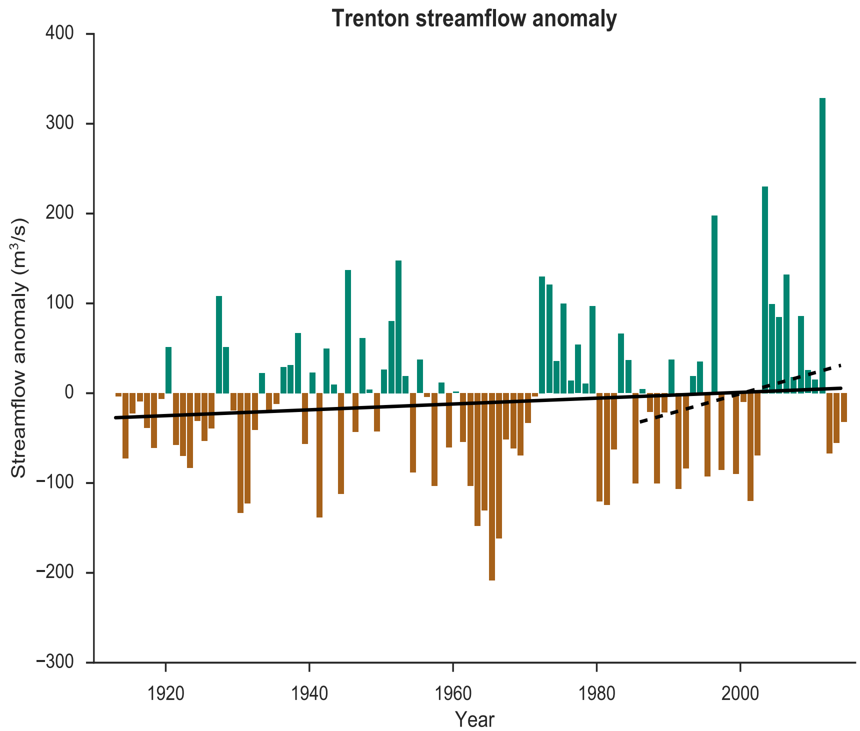

Figure 7.6.1 Time series of annual average streamflow anomaly (with respect to the 1981–2010 average of 349 $m^3 \cdot s^{-1}$ at Trenton, NJ. The solid and dashed lines are linear trends for the 1913–2015 and 1986–2015 periods, respectively.

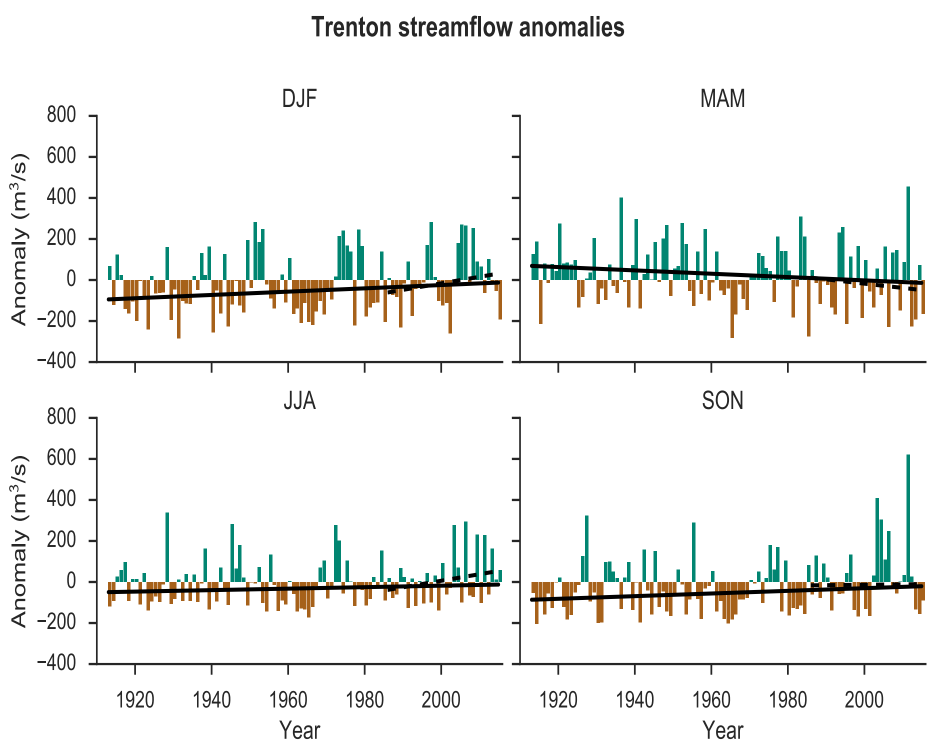

Figure 7.6.2 Time series of seasonal mean streamflow anomaly (with respect to the 1981–2010 average) at Trenton, NJ. The solid and dashed lines are linear trends for the 1913–2015 and 1986–2015 periods, respectively.

The trends at Trenton are similar to the trends observed at the smaller tributaries (Fig 7.6.3). Although only a few trends are statistically significant, negative trends in spring mean streamflow are present at all ten gauges. In the remaining seasons, positive trends are present at every one of the ten gauges except one in winter and two in summer.

7.6.3 Future predictions

Hydrological model simulations forced by global climate models project decreasing runoff from April through November in some areas of the DRB (Williamson et al. 2016). Annual mean runoff, however, is predicted to increase, primarily as a result of increased winter precipitation (Williamson et al. 2016). Model simulations of the nearby Chesapeake Bay watershed also show increasing winter runoff, although a decrease in annual mean runoff becomes more likely with higher emissions scenarios and later time periods (Hawkins 2015).

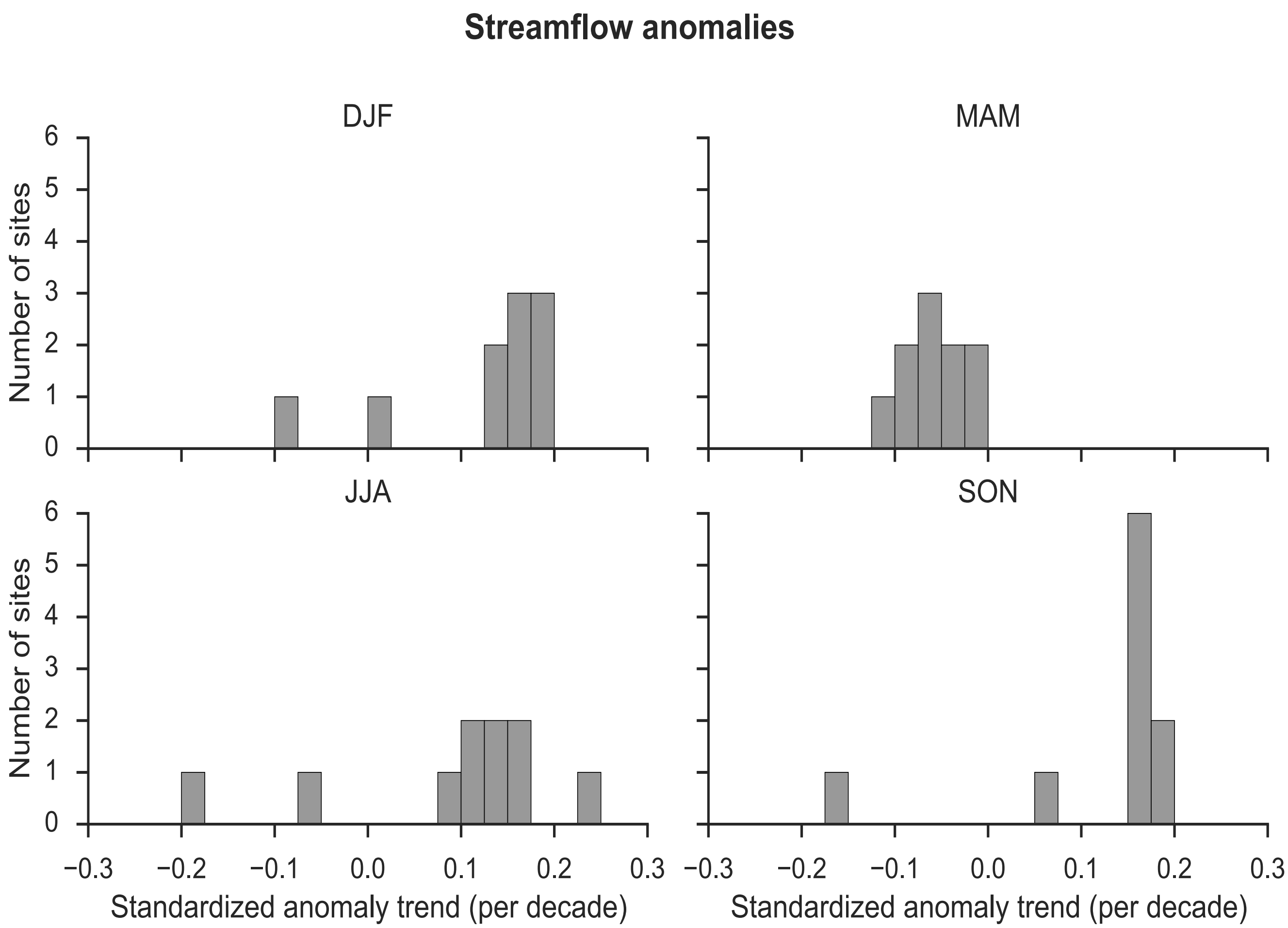

Figure 7.6.3 Histograms of trends in standardized seasonal streamflow anomaly at the 14 tributary sites during 1958-2014.

7.6.4 Actions and needs

Continued monitoring of stream and river flows is critically important to track changes in the water budget of the DRB, which affects estuarine salinity and freshwater availability for people and the environment. Future changes in flow, particularly in summer, are likely to be driven by a combination of precipitation and evapotranspiration changes, which may not be simulated well by global climate models, so understanding and accounting for uncertainty in future flow is necessary.

7.6.5 Summary

Most streamflow trends in the Delaware River and its tributaries are not statistically significant. In the future, increased streamflow is expected in winter and early spring, primarily as a result of increased precipitation, and reduced streamflow in the summer is possible.

7.7 Ice jams

7.7.1 Description of indicator

Occurrences of ice jams were obtained from the Ice Jam Database of the U.S. Army Cold Regions Research and Engineering Laboratory (White 1996). The database contains reports of ice jams in numerous rivers of the northern United States. This section analyzed annual counts (by water year) of ice jams occurring on any river within the DRB and counts of ice jams occurring only on the Delaware River.

7.7.2 Past trends

The number of ice jams that have been reported over the past 85 years in the DRB and in the Delaware River has been declining (Fig 7.7.1). This is possibly a result of underreporting of ice jams in the more recent past (White 1996). However, winter warming of the watershed has occurred, which is expected to lead to fewer ice jams. Indeed, as figure 7.7.2 shows, there is a strong negative correlation between the number of ice jams and the winter mean temperature.

7.7.3 Future predictions

It is reasonable to expect fewer ice jams in the future due to predicted higher winter temperatures. Ice jam frequency shows a strong negative correlation with mean winter temperatures in the DRB.

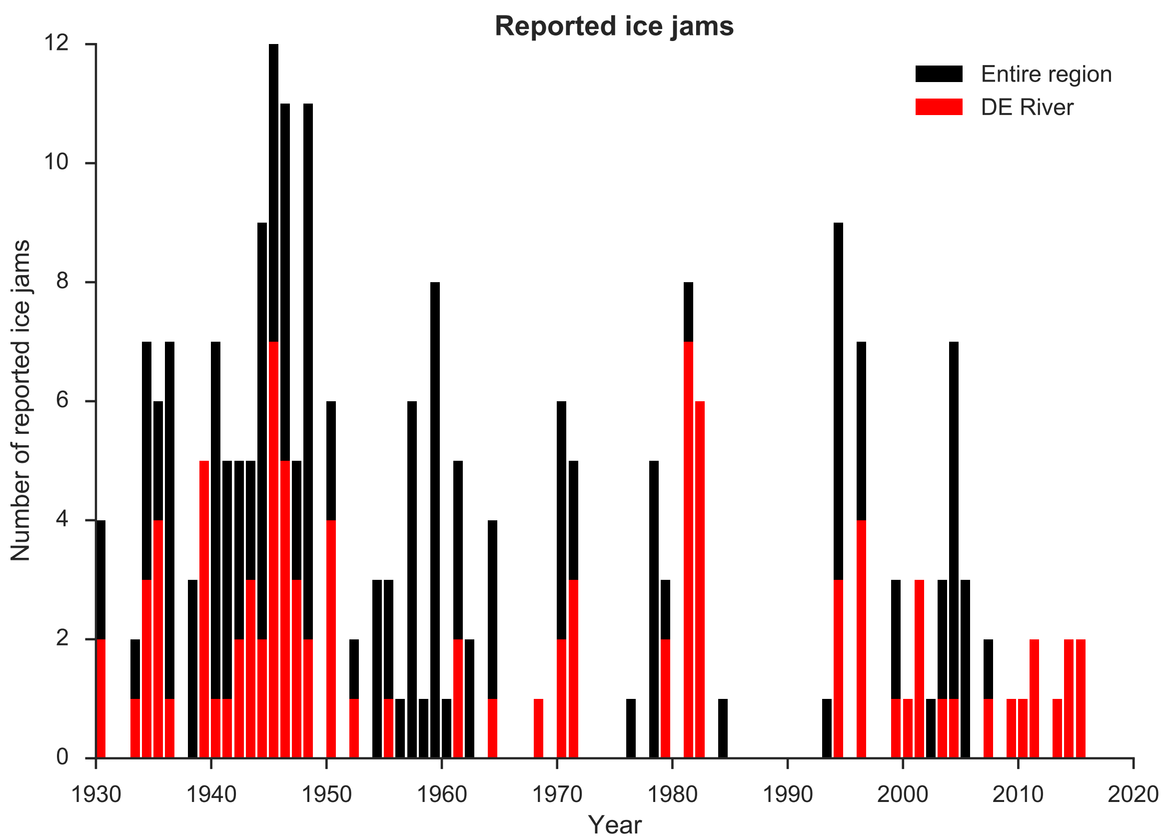

Figure 7.7.1 Annual count of ice jam reports anywhere in the Delaware River Basin (black) and only in the Delaware River (red).

7.7.4 Actions and needs

More analysis is warranted to understand the connection between temperature, river flow, snowfall, and ice jam data quality and consistency. This indicator appears to serve as a useful indicator of a climate change "outcome" and should be further explored.

7.7.5 Summary

Ice jams represent an interesting "outcome" indicator for tracking climate change effects, but the tracking of ice jams has potentially been inconsistent and so the analysis here should be considered as preliminary. Nevertheless, the frequency of ice jams in the DRB has apparently decreased significantly, and the decline is directly correlated with the increasing mean winter temperature across the watershed. Since winter temperatures are predicted to increase markedly in the future, ice jams are likely to become still less frequent.

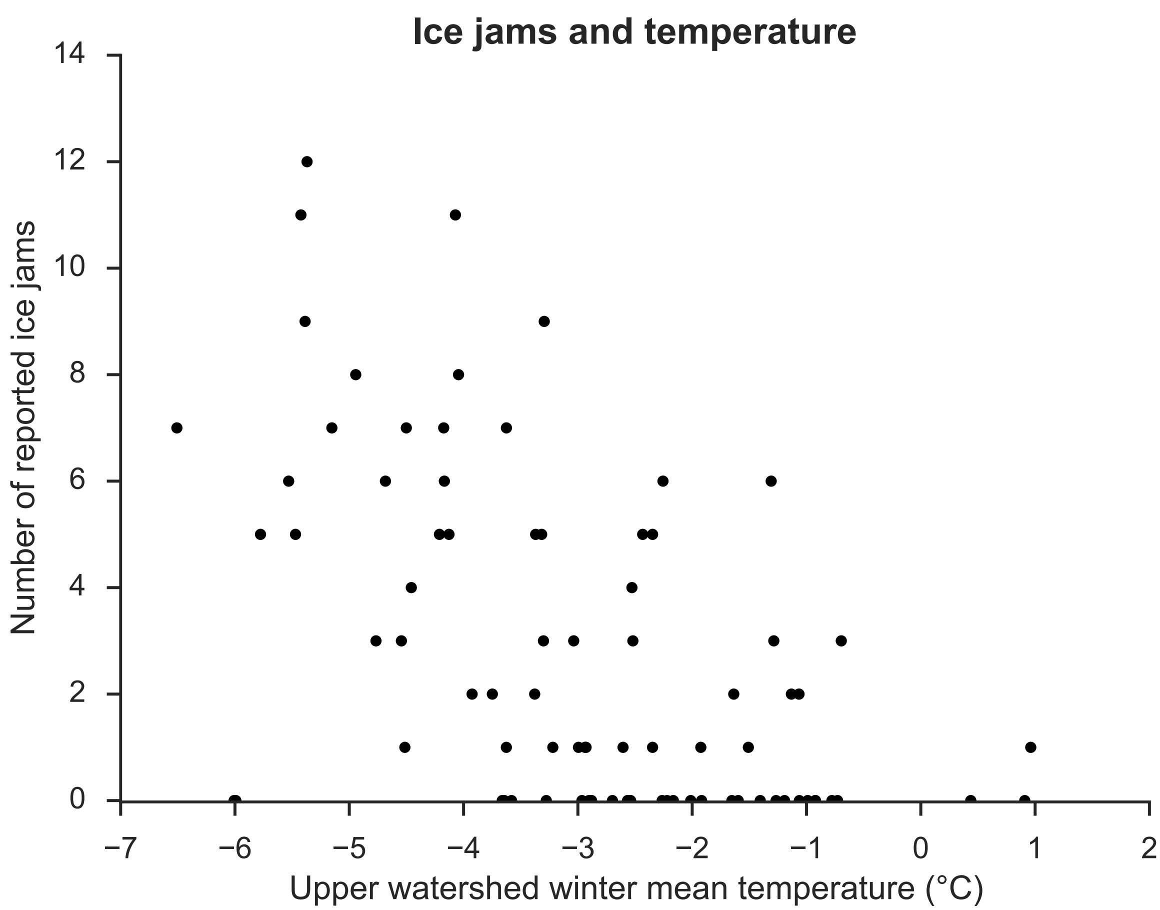

Figure 7.7.2 Annual count of ice jam reports anywhere in the DRB versus upper watershed winter mean temperature.

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Suggested Citation for this Chapter

Ross, A., R. Najjar. 2017. "Chapter 7 - Climate Change" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07 pp. 300-334.

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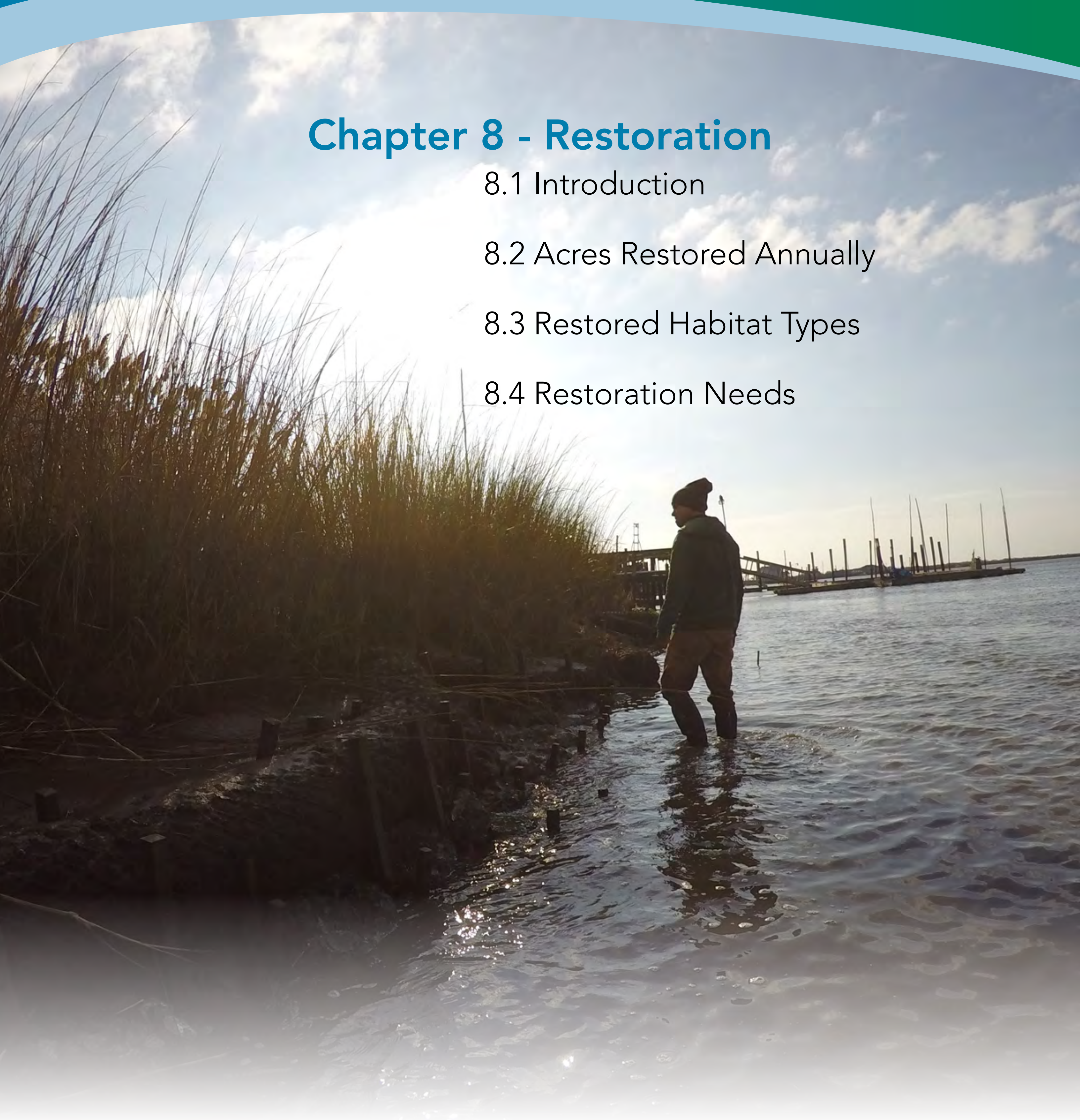

Partnership for the DELAWARE ESTUARY

December, 2017 | Report No.17-07

A publication of the Partnership for the Delaware Estuary—A National Estuary Program

8. Restoration

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Partnership for the Delaware Estuary

8.1 Introduction

The objective of this section is to provide information on restoration efforts and progress in the Delaware Estuary. Whereas Chapters 1 to 7 review the status and trends of environmental indicators as a way to assess the current health of the Delaware Estuary River and Basin, this chapter reports on the success of collective efforts to improve environmental conditions via management actions that protect, enhance, and restore the system. Although, no entity has quantified the cumulative management and restoration progress across the entire Basin, an initial summary of management and restoration progress was provided for the lower basin in our 2012 Technical Report for the Delaware Estuary and River Basin. The indicators presented in this chapter similarly summarize progress achieved in the lower Basin by the Partnership for the Delaware Estuary and collaborators in the Delaware Estuary Program. These should therefore be regarded as baseline measures to be expanded in future assessments of management progress.

Restoration data from multiple states and programs are challenging to collect and analyze. This report uses the most recent restoration project tracking data routinely collected for the National Estuary Program. Future efforts to assess management and restoration progress can be strengthened with further development and implementation of new project tracking tools which have been piloted by the Partnership for the Delaware Estuary, some of which are discussed in this chapter.

In common usage, the term "restoration" implies some form of remediation or improvement that returns a resource to some former condition or location. In some cases, however, targeting historic conditions is inappropriate because the viable location for a resource or habitat may have shifted in response to changing environmental conditions (e.g., salinity, tidal inundation, temperature). In other cases, the structure and function of restored systems may never match that of undisturbed systems, and various tools are used to set appropriate criteria that defines a project's success. In acknowledging our inability to fully repair disturbed systems, restoration practitioners have adopted various definitions of restoration and restoration-type activities. For example, in its 1992 report, Restoration of Aquatic Ecosystems, the National Research Council defined restoration as the "return of an ecosystem to a close approximation of its condition prior to disturbance." The Society for Ecological Restoration defines ecological restoration as "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed."

The concept of restoration is further clarified by defining many types of restoration-related activities. There are many management actions that can be considered as restoration activities, such as land and habitat protection, flow management and pollutant regulation. However, for the purposes here, "restoration" refers to on-the-ground actions that either create, enhance, or restore natural resources. With more precise and expansive data provided in the future, management progress could be broadened to include any actions or decisions that lead to improvements in environmental conditions as assessed by the indicators in Chapters 1-7. This includes the elimination or reduction of stressors that degrade natural conditions. In addition to traditional restoration of past natural conditions, the following terms describe activities that are considered as part of restoration for the purposes of this chapter.

Establishment (also referred to as "creation") is the manipulation of physical, chemical, or biological conditions to facilitate development of a target habitat that is representative of natural conditions but that did not previously exist at the project location. Establishment results in acres gained for the target habitat. For example, establishment occurs when a wetland is placed on the landscape by some human activity on a non-wetland site (Lewis, 1989). Typically, established wetlands are created by the excavation (or addition) of upland soils to achieve elevations that will support the growth of wetland species through the establishment of appropriate hydrology.

Reestablishment is the manipulation of physical, chemical, or biological characteristics of a site with the goal of returning natural/historic habitat types and functions to the site (Fig 8.1.1). Reestablishment results in the rebuilding of a former habitat and a gain in acres for that target habitat.

Figure 8.1.1 Example of reestablishing a riparian buffer along a tributary in the Delaware Estuary. Photo Credit: USDA-NRCS-New Jersey.

Enhancement is the manipulation of physical, chemical or biological characteristics of a site to strengthen ecological conditions and functions, such as for the purpose of improving water quality, flood water retention, or wildlife habitat. Enhancement typically results in improvement of structure and/or function without an increase in acreage (Fig 8.1.2).

Rehabilitation is similar to enhancement and is defined by the USEPA as the manipulation of the physical, chemical, or biological characteristics of a site with the goal of repairing natural/historic functions of a degraded habitat. Rehabilitation results in a gain of habitat function but does not result in a gain of acres for that habitat.

In all types of restoration, changes in ecosystem conditions should result in a net gain or improvement in those ecosystem functions that are deemed of highest value by managers. Since the environmental conditions at any location never have zero value, scientists and managers must recognize that any manipulation results in tradeoffs with respect to living resources, and functions. Efforts to control mosquito populations and improve fish habitat by digging ditches in wetlands could result in decreased vegetation cover and carbon sequestration services. Efforts to eradicate invasive forms of the common reed, *Phragmites australis,* to improve fish and wildlife habitat could result in decreased flood protection and carbon sequestration. Restoration activities therefore ultimately reflect value judgments that can differ among

Figure 8.1.2 Example of stream bank stabilization, showing how extreme measures (e.g. use of rock) is sometimes needed to stem erosion and loss of sediment in cases where upstream sources of stormwater runoff are not also curtailed. Photo credit: USDA-NRCS-New Jersey.

different sectors of the science and management community. Our goal is to quantify restoration progress that reflects the current consensus view on ecological priorities, focusing on key natural resources that typify the Delaware Estuary and River Basin.

Activities that might be considered restoration progress but which do not necessarily fit the definition of restoration given above include the following:

Protection is defined as the removal of a threat to, or preventing the decline of, natural healthy environmental conditions. This includes management actions such as land acquisition for public parks, conservation easements, deed restrictions, etc. or other designations to prevent alteration of natural site conditions. This term also includes activities commonly associated with the term "preservation." Although protection efforts are critically important for sustaining ecological function, they do not result in a net habitat gains.

Mitigation refers to the "restoration, creation, or enhancement of wetlands to compensate for permitted wetland losses" (Lewis, 1989). Here, we also extend that definition to include other natural habitats. For example, under Section 404 of the Clean Water Act, wetlands may be legally destroyed, but their loss must be compensated by the restoration, creation, or enhancement of other wetlands. In theory, this strategy should result in "no net loss" of wetlands. Other programs that are similar include the Natural Resource Damage Assessment (NRDA) Process and Supplemental Environmental Projects (SEPs). Whether mitigation is successful or not, the goal is to simply replace or repair injured natural resources, meaning that these activities do not (and in some cases legally cannot) result in net gain of habitat acreage or functions relative to pre-injury conditions.

Nature-Based Infrastructure is a relatively new term used to describe engineered projects that intend to build resilience or promote other ecosystem services by taking advantage of physical, chemical, and biological properties of natural systems and assemblages of organisms. Nature-based infrastructure projects differ from ecological restoration in that they are designed and constructed to achieve specific societal or management goals, such as erosion control. In the wake of Superstorm Sandy, nature-based infrastructure has increasingly been promoted for its ability to increase coastal resilience to storms (Cunniff and Schwartz 2015, Weinstein and Saleh 2016). The US Army Corps of Engineers has also acknowledged the value of nature-based infrastructure, differentiating it from natural restoration (USACE 2015). Nature-based infrastructure projects include a broad spectrum of tactics and range from green (biology-based) to gray (hybrids that include a mix of biology and traditional "hard" structures). When successful and maintained, nature-based infrastructure projects can help avert the loss of habitat acres and result in a gain of habitat function, but they typically do not result in a gain of acres for that habitat.

The approach taken in this chapter was to report available indicators that reflect restoration activities across the Delaware Estuary and Basin, focusing on metrics that can be quantified such as acres, locations, and types of habitats restored and available data. It's important to note that in contrast to these restoration activities, many important habitats are continuing to be lost or degraded (see Chapters 1 and Chapter 5). Therefore, on balance, the net loss of key natural habitats (e.g. forests, wetlands) continues to be substantial, despite these restoration successes.

8.2 Acres Restored Annually

8.2.1 Description of Indicator

Many important resources are found in the Delaware River Basin. For example, the Estuary contains more than 150,971 acres of wetlands, more than 51,252 of which are recognized as internationally important (Tiner et al., 2011). The tidal portion of the system is also one of the largest freshwater tidal estuaries in the world, and despite losing >95% of rare freshwater tidal wetlands, the system still has more acres of this habitat type than anywhere else in the United States. The Delaware Estuary also has 185 natural vegetation community types encompassing 35 broader-scale ecological systems. Delaware Bay contains the largest breeding population of horseshoe crabs (*Limulus polyphemus*) in the world. The watershed also contains critical habitat for endangered populations of dwarf wedgemussels (*Alasmidonta heterodon*), two species of sturgeon (*Acipenser oxyrinchus* and *A. brevirostrum*), and bog turtles (*Glyptemys muhlenbergii*).

Considering the tremendous habitat diversity, numerous geopolitical boundaries, and large size of the watershed, efforts to track restoration progress are hampered by limited data availability among the many different agencies and programs that are responsible for restoration across this large watershed. One of the most straightforward ways to track habitat restoration is to determine acres restored annually, focusing on voluntary actions (and not reparative, regulatory based actions such as mitigation projects). Ideally, restoration activities should also be assessed for specific habitat types. In the future, it would be beneficial to also assess the functionality to restored habitats, since a particular site could be "restored" significantly without any net increase in acreage. Since no database exists to track watershed-wide restoration, as a starting point for this effort, we discuss acreage data that have been reported as restored (and/or protected) by each state (New Jersey, Pennsylvania, and Delaware) annually using the USEPA's National Estuary Online Reporting Tool (NEPORT).

NEPORT is a web-based database that USEPA developed for National Estuary Programs (NEPs) to track the acreage of habitat improvement efforts. The Partnership for the Delaware Estuary has been collecting data on completed restoration projects from partners (mainly state agencies and PDE initiated projects) since 2000 to report to the USEPA annually. The USEPA then provides the project information for every National Estuary Program on this website: http://www.epa.gov/owow_keep/estuaries/pivot/mapping/sat.html and the NEP map website: https://gispub2.epa.gov/NEPmap/.

Core Partners of the Delaware Estuary Program that provide data for NEPORT
Pennsylvania Department of Environmental Protection
Philadelphia Water Department
New Jersey Department of Environmental Protection
Delaware Department of Natural Resources and Environmental Control

Unfortunately, NEPORT is not comprehensive as it only shows project data that have been voluntarily provided by core partners of the Partnership for the Delaware Estuary. Since there are many other restoration activities and organizations and NEPORT data focus only on the lower half of the Delaware River Basin, data for this indicator therefore represents only a fraction of restoration progress at the watershed scale. However, since this approach has been followed for more than ten years, it is possible to examine trends in restoration progress using NEPORT-tracked restoration as an indicator. However, it should be noted that USEPA does occasionally make changes to the NEPORT data collection and reporting process, and this can impact the data. Another advantage of NEPORT data is that the tracking program excludes actions associated with mitigation (e.g. Natural Resource Damage Assessment, Supplemental Environmental Project), which are designed simply to correct for discrete injuries. Although protection efforts are not the focus of this chapter (see above), NEPORT data for protected acreage are also shown here for comparison purposes.

8.2.2 Present Status

Recent restoration progress was examined qualitatively by contrasting the types of efforts made in the Delaware Estuary from 2006-2016, as reported in NEPORT. NEPORT tracks restoration as either protection, rehabilitation, enhancement, reestablishment, or establishment. The relative balance of these activities (Fig 8.2.1) indicates that considerably more land area has been protected than restored. Among the five types of restoration tracked in NEPORT, more area was enhanced than rehabilitated or reestablished, and newly created acres (establishment) represented a very small portion of overall efforts.

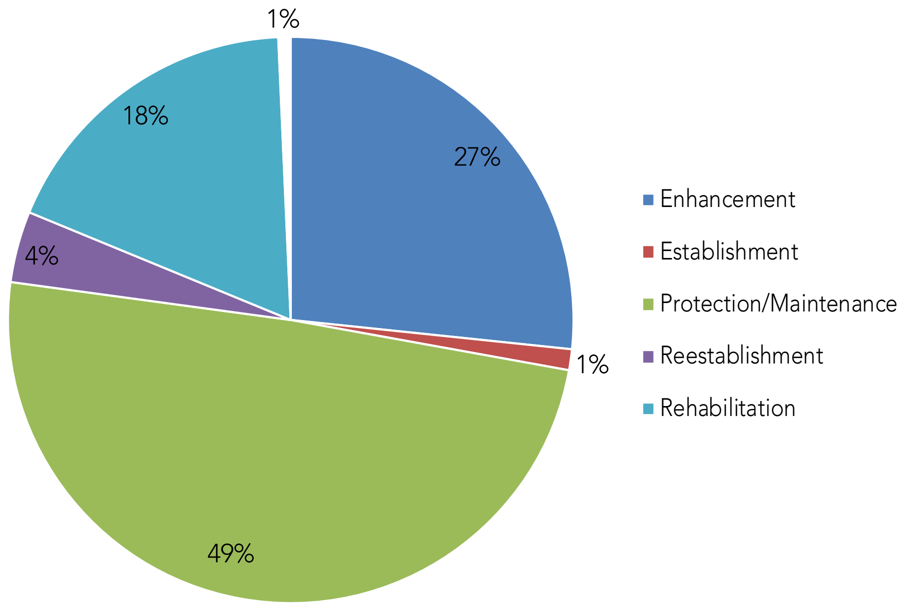

Figure 8.2.1 Comparison of the land area protected versus restored between 2006 and 2016, as reported in NEPORT percent of acres.

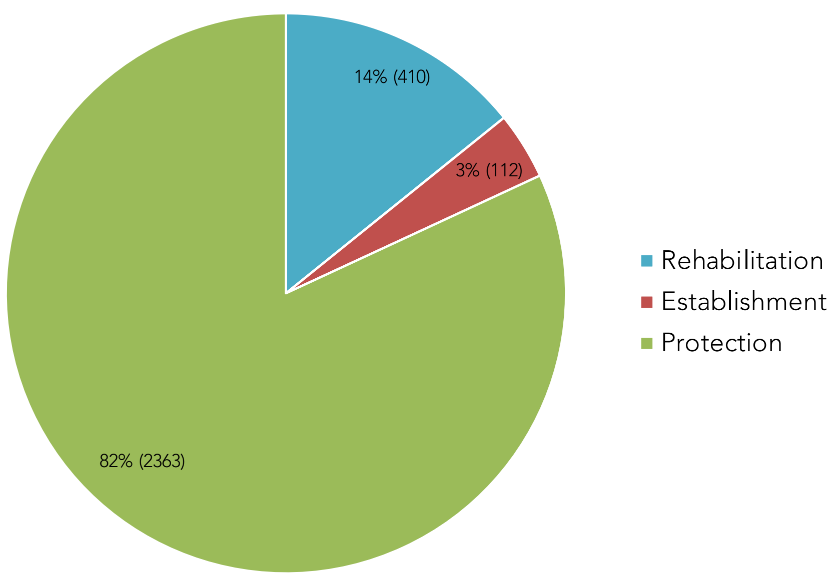

Figure 8.2.2 Comparison of the percent of total acreage that was protected versus restored in 2016, as reported in NEPORT.

As noted above, protection does not necessarily improve ecological conditions. Therefore, summing acreage data from NEPORT does not give a clear representation of actual net ecological improvement since so much of what is reported took the form of protection (Fig 8.2.1). This finding is even more important for the most recent NEPORT data from 2016 (Fig 8.2.2), which shows that protection accounted for more than three-quarters of the total activity. Since yearly acreage data can be skewed by 1 or 2 large projects, a fuller understanding of status and trends should examine the nature of specific projects reported via NEPORT.

8.2.3 Past Trends

As a National Estuary Program, the Partnership for the Delaware Estuary (PDE) is responsible for setting restoration goals every year. Since the advent of NEPORT tracking in 2000, the total number of acres reported to NEPORT each year represent a modest 0.017% of the total area of the Delaware River Basin. As noted above, tracking restoration is challenging because PDE must rely on voluntary reporting by partners. Annual variation in restoration investment also takes place since projects are typically grant-funded and are subject to funding fluctuations. Despite these caveats, restoration progress since 2006 has been considerable (Fig 8.2.3), typically exceeding the annual goal set by PDE and USEPA for the combination of protected and restored acres. Prior to 2011, this annual goal was 2,250 acres. Due to declining acreage that was protected or restored between 2007 and 2010, this annual goal was changed in 2011 to be 1,500 acres. In most years since 2006, protection efforts surpassed restoration efforts, largely due to data reporting from programs such as New Jersey Green Acres that provides funding for land acquisition projects. The 1,500-acre goal is set annually by NEPs to capture projects conducted by partners in the region (Fig 8.2.3). This value can be adjusted by the NEPs reporting out to USEPA based on their understanding of current restoration projects taking place during the reporting year, and is set at a different value for all of the NEPs.

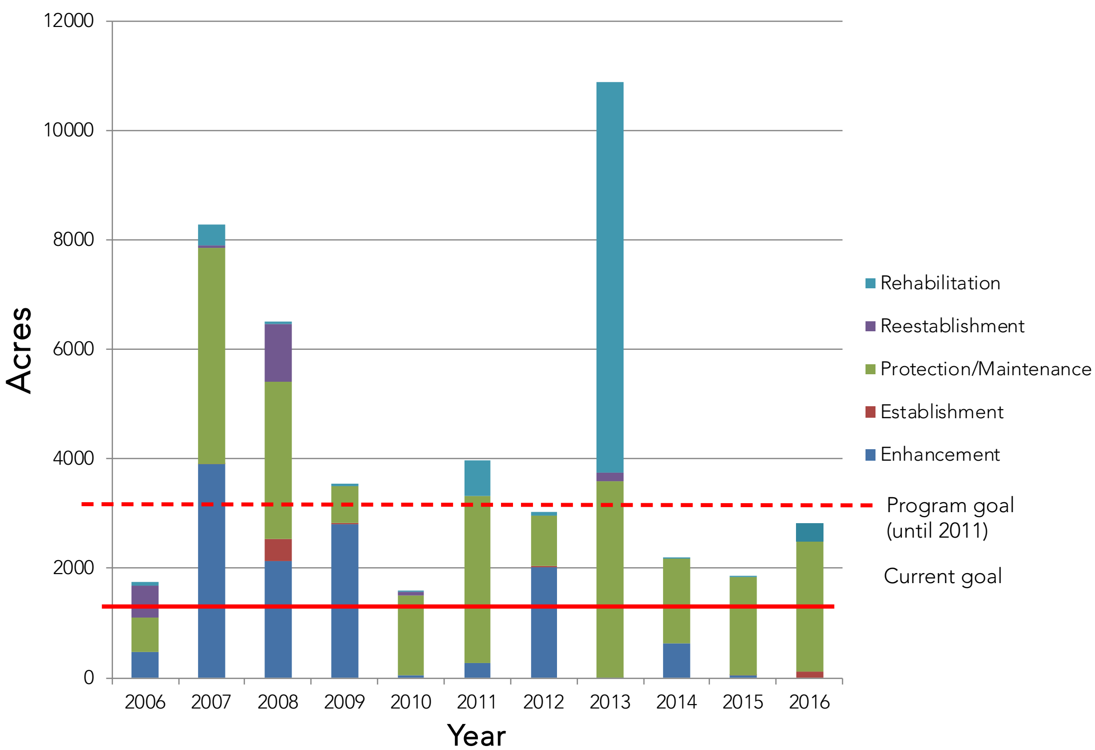

Figure 8.2.3 Acres restored and protected annually between 2006 and 2016, with five types of restoration reported separately. For comparison, the annual NEPORT goals are shown for the 2006-2010 (dashed red line) and 2011-2016 periods (red line).

8.2.4 Future Predictions

The amount of area restored per year in the Delaware Estuary (per NEPORT) through non-mitigation, voluntary actions is dependent on funding, especially from state and federal agencies. The restoration need is high, as judged by the continuing losses of critical habitats. However, we are optimistic that in the long term, the pace of restoration will hasten as our understanding of the ecological and economic consequences of inaction increases. For example, water resources in the Delaware Estuary sustain a $10 billion per year economy, and the loss and degradation of natural systems is certain to have serious economic consequences (Kauffman 2011). In the short-term, we anticipate that restoration progress could be undermined if federal investment in environmental programs is reduced, as has been proposed. Fortunately, non-profit organizations such as the William Penn Foundation have recognized the importance and scale of the restoration need, contributing substantial resources to create a new Delaware River Watershed Initiative that is supporting habitat restoration in many areas (WPF 2014). With sustained or increased investment by other state and local entities, and potentially new public-private partnerships, we anticipate that the Delaware Estuary Program will continue to meet the annual 1500-acre goal.

8.2.5 Actions and Needs

Unfortunately, hundreds of thousands of acres of natural habitats have been destroyed or significantly altered in the Delaware River Basin during the past 15 years despite many governmental protections. Losses of forest area due to development (Chapter 1) and erosion of coastal wetlands (Chapter 5) appear to far exceed gains from restoration. Since these natural habitats purify our water, provide clean air to breathe and furnish other critical goods and services enabling the survival of both humans and natural communities, this trend in net loss of natural habitats is unsustainable, especially considering projections for human population growth (Chapter 1.1).

One of the top goals in the Comprehensive Conservation Management Plan for the Delaware Estuary (CCMP) is the restoration, protection and enhancement of natural habitats. Therefore, it is vital that funding and commitments be sustained and increased for implementation of the CCMP by the various partners of the Delaware Estuary Program. Over the past few decades, federal investment in environmental programs and restoration in the Delaware River Basin has vastly lagged behind other large watersheds in the United States, estimated to be between 1-2% per capita or per basin area. To stem current rates of loss of key natural habitats, this investment needs to be increased or offset by non-federal efforts. Considering the limited restoration funding and high need, careful prioritization is essential so implemented projects target the most critical needs for maintaining core ecosystem functions (PDE 2005, 2009, Kreeger et al. 2006). All citizens in the Delaware River Basin can also play a part in promoting voluntary restoration and protection of our remaining natural habitats. Some ways in which citizens can get involved includes volunteering at cleanups, invasive species removal projects and participating in community restoration projects.

8.2.6 Summary

Quantitative measures of land area restored annually in the Delaware Estuary can be an effective way to track management progress, and analysis of limited data suggests that some progress has been made since 2006. However, the current tracking system used by the Partnership for the Delaware Estuary (NEPORT) is not designed to be comprehensive for the watershed, and it gives a biased estimate of the amount and type of restoration in the Estuary. It is useful as a progress indicator because annual data collection has been consistent for a sufficient period to examine trends, showing that generic restoration targets set by the National Estuary Program have been met. Improvements in such reporting would be to strengthen future status and trends reporting on management progress. Although NEPORT data significantly underestimates actual restoration investment across the entire Delaware Estuary and Basin, the amount of land area restored between 2006-2016 is likely dwarfed by mounting losses of natural lands due to development and other factors. For example, the land use land cover changes described in Chapter 1 clearly suggest that management progress via restoration is not keeping pace with overall needs to sustain core habitats.

8.3 Restored Habitat Types

8.3.1 Introduction

In addition to assessing the amount of area restored, it is helpful to track the types of habitat that are being restored to ensure that restoration progress reflects the balance of habitats that have suffered the most degradation. For example, coastal wetlands are a hallmark feature of the Delaware Estuary, and are critical for supplying diverse benefits to people and the environment, and we have lost more than half of our coastal wetlands mainly due to direct filling and development (Chapter 5.2). Forests are similarly vital for sustaining source water quality and other services, and forest losses continue to be swift due to development (Chapter 1.3). Similar to Section 8.2, data from the National Estuary Program Online Reporting Tool (NEPORT) was examined to discern the types of habitats that have generated the greatest restoration attention since 2006.

8.3.2 Description of Indicator

Healthy estuaries depend on a complex mix of habitats, with each estuary possessing unique character and habitat assemblage. Although the Delaware Estuary and Basin is home to dozens of different habitats and ecological communities, it is most distinct because of its abundant, protective forests in the headwaters, broad freshwater tidal area that supports rare biotic assemblages, and a wealth of coastal wetlands that fringe the tidal estuary. These systems purify our water, provide clean air to breathe, and furnish other critical goods and services enabling the survival of both people and natural communities. To get the greatest benefits, voluntary (non-mitigation) attempts to rebuild these habitats should reflect the natural balance of types that characterizes the watershed.

8.3.3 Present Status

Figure 8.3.1 shows a comparison of all the acres restored between 2006 and 2016 by habitat type. Tidal wetlands and forests have been the focus of management attention since 2006, judging from the combined data for restored habitat types (Fig 8.3.1). Most of the data was collected via efforts to protect and restore tidal wetlands represented the greatest progress (see Section 8.2).

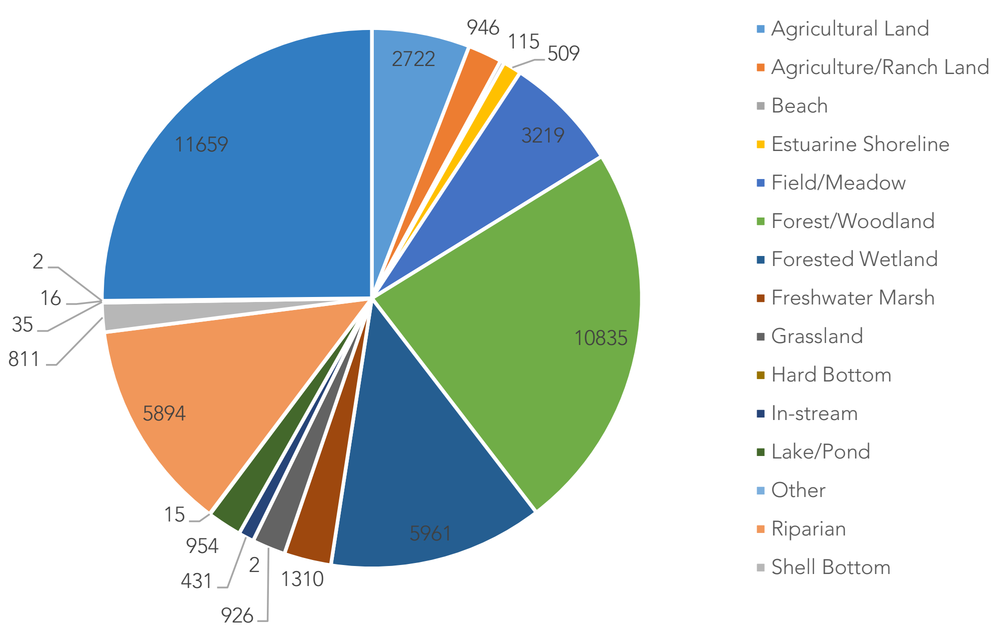

Figure 8.3.1 Comparison of acres restored and protected by habitat type between 2006 and 2016 as reported in NEPORT, numbers are in acres.

As noted in Chapter 5.2, more than half of tidal wetlands have been lost in the Delaware Estuary compared to pre-settlement condition. Between 1996 and 2010, nearly 2% of tidal wetland acreage was lost (Chapter 5.2). Future projections suggest that 119,000 acres (48,000 hectares) will be lost by 2100, assuming that sea level rises by one meter (Kassakian et al. 2017; Kreeger et al 2010). Forests continue to be lost at an even faster rate (Chapter 1.3), and the cumulative impacts from the development of numerous small parcels and pipelines (Fig 8.3.2), and other contemporary challenges threaten to hasten loss rates in the future. Continued focus on tidal wetlands and forests is therefore warranted. Other habitats that have been prioritized such as shellfish beds are arguably even more vital, but they are also smaller in size and harder to capture in terms of acres.

Figure 8.3.2 Example of forest cutting to make wat for a new pipeline near Aston, PA, during October 2017. Photo credit: Danielle Kreeger, Partnership for tthe Delaware Estuary.

8.3.4 Past Trends

The amount of area protected and restored varies widely among years and among habitat types (Fig 8.3.3). This variability is due mainly to fluctuations in funding from year to year, as well as shifts in reporting from various state and local partners who report data to NEPORT. Although it is difficult to draw any conclusions from these limited data, there is an apparent downward trend in the total acreage restored and protected. It is possible that this trend might simply reflect reporting variability or effectiveness rather than real patterns. Nevertheless, the trend is concerning as natural habitat losses have not similarly declined (Chapter 1.3) and the apparent decline in restoration and protection progress is therefore not due to reduced opportunities.

8.3.5 Future Predictions

In the short-term, we anticipate that overall restoration progress could continue to be hampered by a declining level of federal investment in environmental programs, as noted in Section 8.2.4. Conversely, damages from Hurricane Sandy and new threats from development and climate change have energized local and regional efforts to sustain and restore natural habitats, such as coastal wetlands that help buffer coastal flooding. The new Delaware River Watershed Initiative (WPF 2014) and Delaware River and Bay Conservation Act (passed in 2016 and pending funding) are examples of other recent support for watershed restoration. As the various benefits of natural habitats to health and prosperity become clearer, the long term prognosis for protection and restoration of natural areas is good. Habitats that yield the greatest ecosystem services (e.g., clean air and water, flood protection) are likely to be prioritized.

8.3.6 Actions and Needs

Given limited funding for natural area restoration in the Delaware River Basin, it is vital that limited investments be spent wisely by prioritizing areas and habitat types that are deemed most critical for preserving the character and functionality of the unique Delaware Estuary watershed and using scientific information to promote the greatest possible success. Several strategic planning initiatives have been

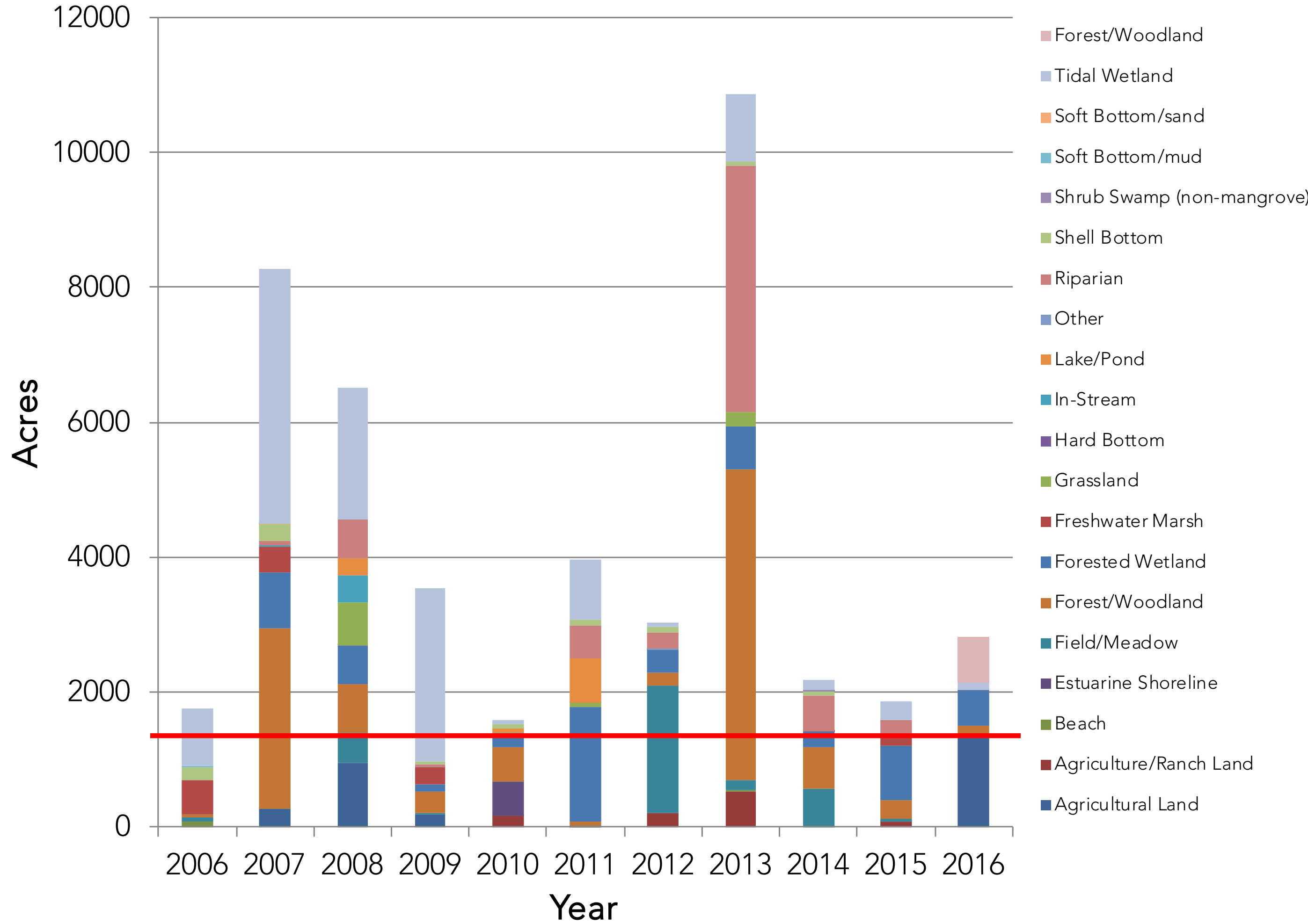

Figure 8.3.3 Total Acres restored annually by habitat type, 2006-2016, in relation to the annual NEPORT goal set by the Partnership for the Delaware Estuary of 1500 acres (red line).

completed in the past 10 years to guide investments in natural habitats at the watershed scale. Some have targeted key species and places with an emphasis on protecting what's left. For example, in November 2011, The Nature Conservancy and partners completed a set of protection and restoration strategies to conserve the Delaware River Basin from the headwaters to the Bay. Their prioritization report (TNC 2011) included various strategies to target high value places in the landscape for protection and restoration. Floodplains, shellfish beds, and habitat preferences of migratory fish were some of their focal resources.

A complementary approach to watershed restoration prioritization has focused on promoting the greatest overall health and functionality of the Estuary's key ecosystems. This ecosystem service approach was articulated in the Regional Restoration Initiative (PDE 2009), which guides future decisions on restoration, protection and enhancement by focusing on habitat types and living resources that furnish core ecosystem goods and services. In addition to habitat type, this approach prioritizes places in the landscape where restoration action can yield the greatest return on investment in the form of natural capital. Urban waterfronts, tidal wetlands, headwater streams, and bivalve shellfish are examples of activities recommended for prioritization.

Another important restoration effort that is underway is being funded by the William Penn Foundation. The partner organizations involved in the Delaware River Watershed Initiative recently completed planning for Phase II (2018-2021), which is expected to lead to diverse new agricultural and stormwater restoration projects within targeted areas referred to as clusters.

These new conservation and restoration prioritization tools that specify habitat types and places to be targeted should be used to guide strategic investments. Continued refinement of these priorities would also benefit from additional research to assess and contrast outcomes from various restoration tactics. For example, living shorelines and thin-layer use of dredge material represent new approaches for stemming losses of tidal wetlands, but project designs and long-term benefits should be scientifically vetted. Similarly, innovative strategies are being tested for managing stormwater and pollutant runoff, such as Philadelphia's Green City, Clean Waters programs. Outcomes from these initiatives will help guide strategic investments in the future.

To facilitate progress implementation and progress tracking, a centralized database for prospective and completed restoration projects would be invaluable. The Regional Restoration Blueprint (PDE 2009) called for the development of this "Project Registry." The registry was created in 2010 and populated with numerous viable pending restoration and protection projects. A workgroup referred to as the Alliance for Comprehensive Ecosystem Solutions was also formed to prioritize projects in the registry for funding. Decisions were based on the estimated natural capital improvement from each project, as determined by a regional restoration subcommittee of the Partnership for the Delaware Estuary's Science and Technical Advisory Committee. This regional restoration effort, including maintenance of the Project Registry, was discontinued in 2013 due to lack of funding. Science-based, regional prioritization and tracking of prospective and completed restoration and protection projects remains a critical need for the Delaware Estuary and River Basin.

8.3.7 Summary

The balance of habitat types restored and protected in the past 11 years can be analyzed with data from the National Estuary Program Reporting Tool. Although results from this analysis should be interpreted with caution because the dataset is limited, restoration progress in the Delaware Estuary appears to be targeting the appropriate habitat types that are considered most vital and which are experiencing greatest losses. Since those losses far exceed the gains from restoration and protection, increased investment and strategic prioritization are warranted.

8.4 Restoration Need

8.4.1 Introduction

The need for more restoration in the Delaware River Basin is sizable based on the disparity between the historic and recent losses in acreage of natural lands (see other chapters) and the relatively small gains in acreage from restoration efforts over the past decade (see Section 8.1). Although science-based planning tools have been recently developed to guide strategic restoration and protection investment at the watershed scale (Section 8.3.5), these tools will be useless without funding to implement new projects to offset losses that go well beyond site-specific, regulatory-based mitigation. This section clarifies restoration need and investment level, and results are contrasted with some other large American "Great Waters."

8.4.2 Description of Indicator

To gauge the current restoration need for the entire Delaware River Basin is a daunting task. One approach is to simply examine the loss rates of key habitats (e.g. wetlands, forests) in other chapters of this report, and infer that those losses should be offset by restoration. However, it is difficult to assign a restoration cost to such large changes and the result would be tremendous (estimated at hundreds of millions of dollars per year) because every year we are losing several square miles of important natural habitats. Natural habitat loss data are more useful for information purposes, providing the impetus for managers to set ambitious restoration targets because they are grounded in tangible data on ecological trajectories of change.

At the other end of the scale, a second approach to gauging restoration is to simply tally the total dollars that would be required to fund all pending protection and restoration projects. As part of the Regional Restoration Initiative (PDE 2009), as Project Registry was created that attempted to capture data on all pending and funded restoration projects in the Delaware Estuary, especially those that focused on high priority habitats and areas. After a successful 3 year pilot, sustained funding for the Initiative and associated registry have not been found and the pending project data are no longer current. When it was last operational in 2013, the registry contained 90 unfunded "shovel-ready" projects totaling over 60,000 acres of possible restoration and budgeted to cost more than 10.5 million dollars, and this was considered to represent only a small fraction of the restoration landscape. Although the project registry data are out of date, they are the most recent example of restoration need for the Delaware Estuary. In addition to the project registry, other organizations have identified restoration project needs, such as witin clusters of the Delaware River Watershed Initiative.

8.4.3 Present and Past Status

The projects listed in the most recent update of the PDE Project Registry (2013) represent only a fraction of total watershed needs to reverse net losses and achieve no net loss of natural lands. Although the projects listed in the 2013 registry aimed to restore or protect 60,000 acres, only about 2.5% (1,500 acres) would have likely been classified as "reestablishment" judging from the array of types of recently completed projects (Fig 8.2.1). Assuming that the 90 projects costing $10.5 million in the 2013 registry would contribute 1,500 acres, then the cost per acre would be $7,000, which is very low relative to typical restoration costs per acre. More than 70,000 acres of forests and wetlands were lost between 1996 and 2010 (Chapter 1), which translates to 4,667 acres per year. Hence, a conservative estimate of the restoration costs just to offset the ongoing forest and wetland losses would be $32,666,667 per year ($7,000 per acre times 4,667 acres per year).

This estimate of $32.7 million per year is simply the cost to sustain the forests and wetlands that we currently have. It does not actually restore historic losses, nor does it account for ongoing losses of other valuable natural habitats to development, such as shellfish beds and agricultural lands. Even if completely funded and implemented, costs will undoubtedly increase because of inflation and mounting development pressures from human population growth and changing climate conditions (e.g. sea level rise, increased intensity of storms). Although this estimate of restoration need is substantial, it represents only 0.3% of the annual worth of the natural resources within the Delaware Estuary (lower half of the Basin), which have been valued as contributing over $10 billion in annual economic activity associated with water quality and supply, hunting and fishing, forestry, agriculture and commercial and recreational fishing, hunting, and other types of recreational activities (Kauffman 2011).

Although the Delaware Estuary and Basin is similar to other large American "Great Watersheds" in supporting a vibrant economy that is linked to natural resources, it is dissimilar in terms of restoration investment. For example, the Northeast-Midwest Institute reported that the level of investment from one example federal agency, the USEPA, was considerably lower in the Delaware Estuary and Basin than eight of the other most significant aquatic systems that are managed discretely (Strackbein and Dawson 2011). This analysis suggests that federal environmental investment in the Delaware system is far less than 10%, perhaps even 1%, of that invested in the Chesapeake system (Fig 8.4.1), despite supporting a similar human population.

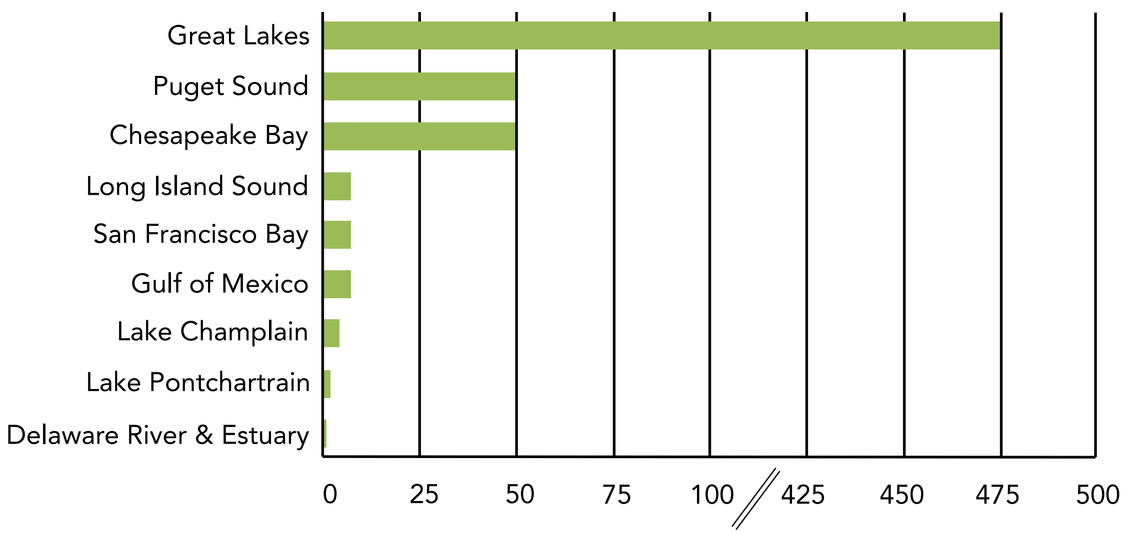

Figure 8.4.1 Comparison of US EPA federal spending in millions ($) for FY2010 on environmental management and restoration in nine major water bodies in the United States (from Strackbein and Dawson 2011).

Restoration investment can also be examined on a geospatial basin, using data from NEPORT (see Chapters 8.1 and 8.2), and this can then be compared with human population in those areas (Fig 8.4.2).

Typically, restoration needs are higher in areas where human population is higher due to habitat degradation associated with pollution, development and other anthropogenic disturbances. Although most people live in the urban portion of the Estuary (Fig 8.4.2), most protection and restoration progress between 2006 and 2016 has been made in less populated areas of the watershed. For example, areas along the Delaware Bay and upper Basin had more investment likely because larger tracts of land can be acquired and protected in these watersheds, and protected acres outnumber restored acres in most years (Fig 8.4.3). This information can be useful for directing the funding for future priority projects, such as by focusing on identifying new opportunities to restore areas in urban landscapes. Further analysis of NEPORT and other data is needed to discern the locations of actual restoration projects. In general, protection is prioritized in less developed areas whereas restoration is prioritized in more developed areas.

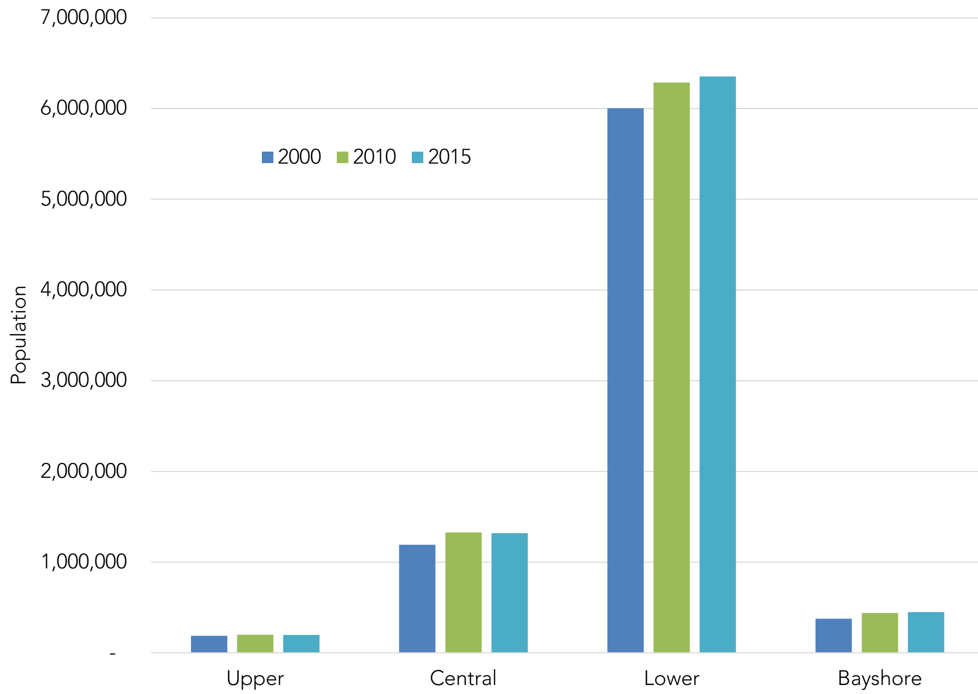

Figure 8.4.2 Comparison of human population in the four watersheds of the Delaware Estuary and Basin (see Fig 0.4).

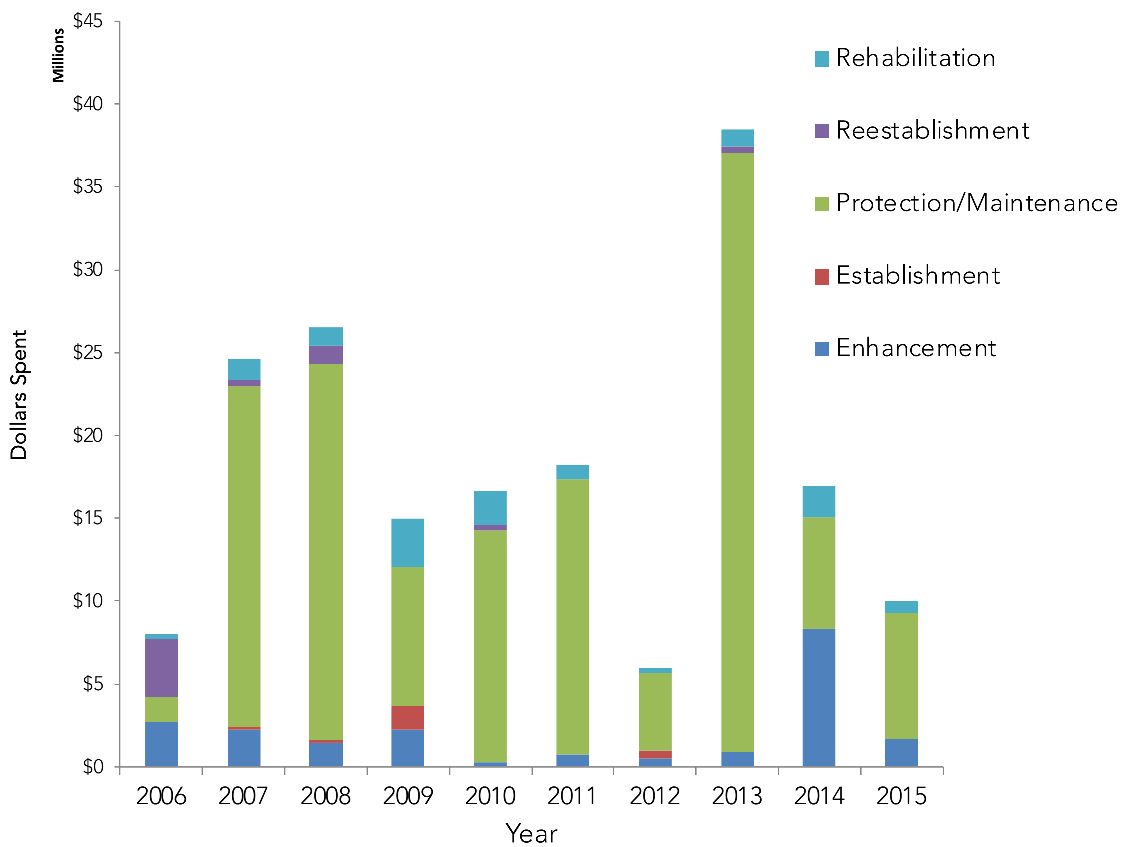

Figure 8.4.3 Comparison of dollars spent from 2006 to 2015 among the different protection and restoration methods.

8.4.4 Actions and Needs

Until sufficient funding can be generated to stem losses of natural lands and restore critical habitats in the Delaware Estuary and Basin, management targets will need to be tempered and continued net losses of vital habitats will unfortunately still occur. As noted above, there are current efforts (PDE and others) to increase efficiency, implement strategic science-based priorities, and coordinate restoration activities. However, these efforts will have limited benefits if restoration needs continue to be largely unmet because of insufficient restoration investment across the Delaware Estuary and Basin.

Thankfully, a substantial amount of new funding for restoration and protection that will benefit many areas is now being contributed by the William Penn Foundation through the Delaware River Watershed Initiative (WPF 2014), showing that non-federal investments are possible and on the upswing since our 2012 Technical Report for the Delaware Estuary and River Basin. But even if that effort can be sustained and the Delaware River and Bay Conservation Act is fully funded, the two new resources will meet less than half of the restoration need estimated here, including some high priority estuary resources (tidal wetlands, shellfish) that are not prioritized in those efforts.

The top restoration need continues to be funding, which can be justified by the economic value of the resources that are being lost every day. Beginning in 2006, the Partnership for the Delaware Estuary proposed the concept of a Delaware Estuary Basin Science & Restoration Trust (Kreeger et al. 2006, PDE 2009), that with sustainable and significant funding, would be capable of addressing diverse restoration needs associated with key living resources, habitats and water resources. Like the Delaware River Watershed Initiative, the Trust is envisioned to be science-based and guided by strategic monitoring and assessment data. The Trust would be maintained and operated by trustees representing federal and state agencies and other groups that have worked together to develop shared, consensus-driven regional restoration priorities. To avoid redundancy with the Delaware River Watershed Initiative and the pending Delaware River and Bay Conservation Act of 2015, priorities addressed by the Trust could fill vital gaps that are not yet being addressed.

In brief, the Trust would provide a new vehicle for accepting and pooling funding from a variety of sources to meet diverse needs, including funding priority restoration and protection projects elevated through the Regional Restoration Initiative. It could include numerous operating centers where contributions could be earmarked for specific protection, restoration, monitoring or scientific activities. The vision is for the Trust to direct and fund wise investments in the future of the Estuary that are not being otherwise supported. Sources of financing for a Trust were explored by PDE with help from the Delaware Community Foundation, the Environmental Finance Center (EFC 2007), the Global Environmental Technologies Foundation, and the Keystone Conservation Trust. The Trust was also identified as a potential means to coordinate watershed-wide restoration funding in the 2013 Regional Sediment Management Plan and the 2010 report by the Delaware River and Bay Oil Spill Advisory Committee. Currently, the Trust is still in the concept stage, and it needs to be further developed and marketed.

8.4.5 Summary

The Delaware Estuary has significant restoration needs, which are conservatively estimated to be greater than $33 million per year. To augment existing investments and fill vital gaps that promote core ecosystem services and the health of local and regional communities, a regional restoration approach is warranted that can prioritize restoration needs, track restoration projects, identify and fill project gaps, and supply funding for high value projects. This will require coordination and sharing among various sectors and development of additional sustainable sources of funding for restoration and protection. A broad-based Science and Restoration Trust would address key gaps in restoration and protection while also providing support for the science and monitoring that is needed to strengthen the scientific basis for restoration decision-making and outcome tracking.

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Suggested Citation for this Chapter

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I. Acronyms and Abbreviations

AMNET	Ambient Biomonitoring Network	Chapter 6
ANCOVA	Analysis of Covariance	Chapter 3
ASMFC	Atlantic States Marine Fisheries Commission	Chapter 6
ASOS	Automated Surface Observing System	Chapter 7
AWR	Annual Wild Rice (*Zizania aquatica*)	Chapter 5
BAT	Barrier Analysis Tool	Chapter 5
BCP	Boundary Control Points	Chapter 3
BDE	Decabromodiphenyl Ether	Chapter 3
BLM	Biotic Ligand Model	Chapter 3
BMP	Best Management Practice	Chapter 4
BOD	Biochemical Oxygen Demand	Chapter 3
C&D	Chesapeake and Delaware	Throughout
C-CAP	Coastal Change Analysis Program	Chapters 1, 5
CCMP	Comprehensive Conservation Management Plan	Chapter 8
CDD	Consecutive Dry Days	Chapter 7
CFS	Cubic Feet per Second	Chapter 2
CMS	Cubic Meter per Second	Chapter 2
COOP	Cooperative Observer Program	Chapter 7
CPMI	Coastal Plain Macroinvertebrate Index	Chapter 6
CPUE	Catch per Unit Effort	Chapter 6
CSC	Cooperative Science Centers	Chapters 1, 2, 4, 5
CSO	Combined Sewer Overflows	Chapter 3
CWCS	Comprehensive Wildlife Conservation Strategy	Chapter 5
DB	Delaware Basin	Chapter 5
DDT	Dichlorodiphenyltrichloroethane	Chapter 6
DE	Delaware	Throughout
DEBI	Delaware Estuary Benthic Inventory	Chapter 5
DE DFW	Delaware Department of Fish and Wildlife	Chapter 6
DELSI	Delaware Estuary Living Shoreline Initiative	Chapter 5, 8

DFW	Division of Fish and Wildlife	Chapter 1
DJF	December, January, February; i.e. winter	Chapter 7
DNREC	Department of Natural Resources and Environmental Control (State of Delaware)	Throughout
DO	Dissolved Oxygen	Chapter 3
DRB	Delaware River Basin	Chapter 7
DRBC	Delaware River Basin Commission	Chapter 2, 3, 4, 6
DRIC	Delaware River Invertebrate Collection	Chapter 5
DRWI	Delaware River Basin Initiative	Chapter 1
DVRPC	Delaware Valley Regional Planning Commission	Chapter 8
DWGNRA	Delaware Water Gap National Recreation Area	Chapter 1
E. Br.	East Branch	Chapter 1
EFC	Environmental Finance Center	Chapter 8
EMAP	Environmental Monitoring and Assessment Program	Chapter 5
ERC	Environmental Research Consultants, Inc.	Chapter 6
ESA	Endangered Species Act	Chapter 6
ETM	Estuary Turbidity Maximum	Chapter 4
EWQ	Existing Water Quality	Chapter 3
FD	Frost Days	Chapter 7
FEMA	Federal Emergency Management Agency	Chapter 5
FFMP	Flexible Flow Management Plan	Chapter 5
GAP	Gap Analysis Program	Chapter 1
GCM	Global Climate Model	Chapter 7
GHG	Global Greenhouse Gas	Chapter 7
GIS	Geographic Information System	Chapter 8
GPCD	Gallons per Capita per Day	Chapter 2
HUC	Hydrologic Unit Code	Throughout
IBI	Index of Biological Integrity	Chapter 6
IC	Impervious Cover	Chapter 1
ICE	Instream Comprehensive Evaluation	Chapter 6
ICP	Interstate Control Points	Chapter 3

IPCC	Intergovernmental Panel on Climate Change	Chapter 5
IRIS	Integrated Risk Information System	Chapter 3
JJA	June, July, August; i.e. summer	Chapter 7
LE	Lower Estuary	Chapter 5
MACWA	Mid Atlantic Coastal Wetland Assessment	Chapter 5
MAM	March, April, May; i.e. spring	Chapter 7
MD	Maryland	Throughout
MDS	Non-Metric Multidimensional Scaling	Chapter 5
MSX	Multinucleated Sphere X; a Disease Caused by *Haplosporidium nelsoni*	Chapter 6
NAC	Northeast Aquatic Connectivity	Chapter 5
NAIP	National Agriculture Imagery Program	Cover pages
NAO	North Atlantic Oscillation	Chapter 7
NCA	National Coastal Assessment	Chapter 5
NCDC	National Climatic Data Center	Chapter 7
NEP	National Estuary Program	Chapter 4, 8
NEPORT	National Estuary Online Reporting Tool	Chapter 8
NJ	New Jersey	Throughout
NJDEP	New Jersey Department of Environmental Protection	Throughout
NJDFW	New Jersey Division of Fish and Wildlife	Chapter 1
NJIS	New Jersey Impairment Score	Chapter 6
NLCD	National Land Cover Dataset	Chapter 1, 4, 5
NOAA	National Ocean and Atmospheric Administration	Throughout
NOEC	No Observed Effect Concentration	Chapter 3
NPDES	National Pollutant Discharge Elimination System	Chapter 1, 3, 5
NRDA	Natural Resource Damage Assessment	Chapter 8
NVCS	National Vegetation Classification System	Chapter 5
NWI	National Wetlands Inventory	Chapter 5
NY	New York	Throughout
NYSDEC	New York State Department of Environmental Conservation	Throughout
PA	Pennsylvania	Throughout

PAD-US	Protected Areas Database of the United States	Chapter 1
PADEP	Pennsylvania Department of Environmental Protection	Throughout
PBDE	Polybrominated Diphenyl Ethers	Chapter 3
PCB	Polychlorinated Biphenyl	Chapter 4, 6
PDE	Partnership for the Delaware Estuary, Inc.	Chapter 0, 5, 6, 8
PFBC	Pennsylvania Fish and Boat Commission	Chapter 6
PMI	Pinelands Macroinvertebrate Index	Chapter 6
PPM	Parts Per Million	Chapter 2
PRM	Potomac-Raritan-Magothy	Chapter 2
PWD	Philadelphia Water Department	Chapter 6
PWS	Public Water System or Public Water Supplies	Chapter 2
RARE	Regional Applied Research Project	Chapter 5
R&D	Research and Development	Chapter 5
RfDs	Reference Doses	Chapter 3
RIBS	Rotating Integrated Basin Studies	Chapter 6
RKM	River Kilometer	Chapter 6
RM	River Mile	Chapter 1, 2, 3
RRI	Regional Restoration Initiative	Chapter 8
RSLR	Relative Sea Level Rise	Chapter 5
SAV	Submerged Aquatic Vegetation	Chapter 5
SEP	Supplemental Environmental Projects	Chapter 8
SEPA GWPA	Southeastern Pennsylvania Ground Water Protected Area	Chapter 2
SL	Sea Level	Chapter 5
SLAMM	Sea Level Affecting Marsh Model	Chapter 5
SON	September, October, November; i.e. fall	Chapter 7
SPW	Special Protection Waters	Chapter 3
STAC	Science and Technical Advisory Committee	Chapter 8
SV	Schuylkill Valley	Chapter 5
TCDD	Tetrachlorodibenzo-p-dioxin	Chapter 3
TCDD	Tetrachlorodibenzodioxin or "dioxin"	Chapter 3

TMDL..Total Maximum Daily Load..Chapter 5

TNC..The Nature Conservancy...Chapter 5, 8

TOC..Total Organic Carbon..Chapter 4

TREB...................................Technical Report for the Delaware Estuary and Basin.............................Throughout

TSS...Total Suspended Solids...Chapter 4

TUc...Chronic Toxic Unit...Chapter 3

UDRSRA................................Upper Delaware River Scenic and Recreational Area..............................Chapter 1

USACE...United States Army Corps of Engineers................................Chapter 2, 4, 6

USDA..United States Department of Agriculture..Chapter 5

USEPA...Environmental Protection Agency..Throughout

USFWS...United States Fish and Wildlife Service..Chapter 5

USGS...United States Geological Survey..Chapter 2, 3

USHCN...................................United States Historical Climatology Network......................................Chapter 7

W. Br..West branch Delaware River..Chapter 1

WET..Whole Effluent Toxicity..Chapter 3

YOY..Young of the Year...Chapter 6

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II. Chapter Authors, Contributors, Datasets, and Suggested Citations

0. Introduction

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Datasets

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1. Watersheds & Landscapes

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Datasets

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1.2 Current Land Cover

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1.5 Public Open Space

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Suggested Citation
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PBDE (Chapter 3.1.8) trend analysis by Kelly Sand, West Chester University student and her academic advisor Charles V. Shorten, PhD, PE in collaboration with DRBC staff.

Datasets

DRBC 24-Hour Mean DO Concentrations <http://drbc.net/Sky/waterq.htm>
DRBC Delaware Estuary Water Quality Explorer <https://johnyagecic.shinyapps.io/BoatRunExplorer/>
DRBC Water Temperature Monitor <http://drbc.net/Sky/waterq.htm>
USGS Continuous Data Monitoring <https://waterdata.usgs.gov/nwis/qw>
USGS monitoring programs <https://water.usgs.gov/owq/data.html>
National Water Quality Data Portal <https://www.waterqualitydata.us/>

Suggested Citation

Yagecic, J., R. MacGilivray. 2017. "Chapter 3 - Water Quality" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 97-145.

4. Sediment

Authors

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Reprinted from Partnership for the Delaware Estuary. 2012. Technical Report for the Delaware Estuary and Basin. P. Cole, A. Padeletti, D. Kreeger (eds). PDE Report No. 12-01. 255 pages.
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Suggested Citation

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5. Aquatic Habitats

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5.1 Subtidal Habitats

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Datasets
Delaware Estuary Benthic Inventory (DEBI) <http://www.delawareestuary.org/data-and-reports/bay-bottom-inventory/>
DelZoop: Delaware Zooplankton Study <https://www.underthescope.udel.edu/project-info>

Reprinted from Partnership for the Delaware Estuary. 2012. Technical Report for the Delaware Estuary and Basin. P. Cole, A. Padeletti, D. Kreeger (eds). PDE Report No. 12-01. 255 pages.
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Suggested Citation
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5.1.9 Delaware Bay Benthic Mapping Project

Author
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Suggested Citation
Wilson, B. 2017. "Chapter 5.1.9 - Delaware Bay Benthic Mapping Project" in the Technical Report for the Delaware estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 175-176**.**

5.2 Intertidal Wetlands

Authors
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Datasets
U.S. Fish and Wildlife Service National Wetlands Inventory <https://www.fws.gov/wetlands/>
NOAA CSC C-CAP <https://coast.noaa.gov/digitalcoast/tools/lca>
NOAA Sea Level Rise Viewer <https://coast.noaa.gov/digitalcoast/tools/slr>.

Suggested Citation
Haaf, L., D. Kreeger, A. Homsey. 2017. "Chapter 5.2 - Intertidal Wetlands" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 177-193.

5.2.9 Annual Variation of *Zizania aquatica*-dominated Marsh Extent: A case study of Mannington Meadows, Salem, New Jersey

Author
LeeAnn Haaf Partnership for the Delaware Estuary

Datasets
Landsat Imagery <http://www.earthexplorer.usgs.gov>
NOAA Sea Level Anomalies <https://tidesandcurrents.noaa.gov/sltrends/sltrends.html>

Suggested Citation
Haaf, L. 2017. "Chapter 5.2.9 - Annual Variation of Zizania aquatica-dominated Marsh Extent: A Case Study of Mannington Meadows, Salem, New Jersey" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 194-195.

5.3 Nontidal Habitats

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Datasets
National Land Cover Dataset <https://www.mrlc.gov/finddata.php>
USACE National Inventory of Dams <http://nid.usace.army.mil/cm_apex/f?p=838:12>

Reprinted from Partnership for the Delaware Estuary. 2012. Technical Report for the Delaware Estuary and Basin. P. Cole, A. Padeletti, D. Kreeger (eds). PDE Report No. 12-01. 255 pages.
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Suggested Citations
Tudor, R., E. Creveling, M. M. DePhilip, C. Pindar. 2012. "Chapter 5.3 - Nontidal Habitats" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 196-212.

6. Living Resources

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6.1 Atlantic Sturgeon

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Suggested Citation
Kahn, D. M. 2017. "Chapter 6.1 - Atlantic Sturgeon" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 215-226.

6.2 Blue Crab

Author

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Suggested Citation

Wong, R. 2017. "Chapter 6.2 - Blue Crab" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 227-232.

6.3 Osprey

Author

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Suggested Citation

Breese, G. 2017. "Chapter 6.3 - Osprey" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 233-235.

6.4 White Perch

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Suggested Citation

Clark, J. 2017. "Chapter 6.4 - White Perch" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 236-240.

6.5 Striped Bass

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Suggested Citation

Hale, E. 2017. "Chapter 6.5 - Striped Bass" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 241-246.

6.6 Weakfish

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Suggested Citation

Greco, M. 2017. "Chapter 6.6 - Weak Fish" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 247-250.

6.7 Horsehoe Crab

Author

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Suggested Citation

Breese, G. 2017. "Chapter 6.7 - Horseshoe Crab" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 251-255.

6.8 American Shad

Author

Gregory Breese, PhD U.S. Fish and Wildlife Service

Suggested Citation

Breese, G. 2017. "Chapter 6.8 - American Shad" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 256-261.

6.8.9 Schuylkill River American Shad Stock Restoration

Authors

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Suggested Citation

Butler, L. and J. Perrilo. 2017. "Chapter 6.8.9 - Schuylkill River American Shad Stock Restoration" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 262-264.

6.9 Eastern Oyster

Author

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Datasets

Rutgers Delaware Bay Oyster Stock Assessment <http://hsrl.rutgers.edu/SAWreports/index.htm>

Suggested Citation

Bushek, D. 2017. "Chapter 6.9 - Eastern Oyster" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 265-270.

6.10 Freshwater Mussels

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Suggested Citation

Kreeger, D. and K. Cheng. 2017. "Chapter 6.10 - Freshwater Mussels" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 271-277.

6.11 American Eel

Author

Jordan Zimmerman

Suggested Citation

Zimmerman, J. 2017. "Chapter 6.11 - American Eel" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 278-282.

6.12 Macroinvertebrates

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Reprinted from Partnership for the Delaware Estuary. 2012. Technical Report for the Delaware Estuary and Basin. P. Cole, A. Padeletti, D. Kreeger (eds). PDE Report No. 12-01. 255 pages. <http://www.delawareestuary.org/data-and-reports/state-of-the-estuary-report/>

Suggested Citation
Burke, D., G. Bright. 2012. "Chapter 6.12 - Macroinvertebrates" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 283-298.

7. Climate Change

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Datasets
U.S. Historical Climatology Network Database <http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn.html>
NOAA's Cooperative Observer Program <http://www.nws.noaa.gov/om/coop/>
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NOAA Atlantic Oscillation Indec <http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml>
National Climatic Data Center <https://www.ncdc.noaa.gov/societal-impacts/wind/>
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Suggested Citation
Ross, A., R. Najjar. 2017. "Chapter 7 - Climate Change" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07 pp. 300-334.

8. Restoration

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Suggested Citation

Kreeger, D., S. Bouboulis. 2017. "Chapter 8 - Restoration" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 336-351.

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