DELAWARE RIVER BASIN PRIORITY CONSERVATION AREAS AND RECOMMENDED CONSERVATION STRATEGIES

Final Report for the National Fish and Wildlife Foundation

The Nature Conservancy, Partnership for the Delaware Estuary and Natural Lands Trust
Funded by the National Fish and Wildlife Foundation
September, 2011

Copies of this report are available in electronic format at http://conserveonline.org/workspaces/nfwfdebasin.
Report and data cd are available by contacting The New Jersey Chapter of The Nature Conservancy at (609) 861-0600.

PROJECT STAFF

THE NATURE CONSERVANCY

Bob Allen
Mark G. Anderson
Ellen Creveling
Mari-Beth DeLucia
Michele DePhilip
Patty Doerr
Su Fanok
Moses Katkowski
Andy Manus
Tara Moberg
Eric Olsen
Mike Shanahan
Joseph Smith

THE PARTNERSHIP FOR THE DELAWARE ESTUARY

Priscilla Cole
Danielle Kreeger

NATURAL LANDS TRUST

Megan Boatright
Ann Hutchinson
Diane Rosencrance
Jim Thorne

TECHNICAL EDITOR

Nancy Steinberg

ACKNOWLEDGEMENTS

The project team would like to especially thank *Greg Breese* (U.S. Fish and Wildlife Service), *David Bushek* (Rutgers University, Haskins Shellfish Research Lab), *Dave Carter* (Delaware Department of Natural Resources and Environmental Control – Coastal Programs), *Gary Cassabona* (Natural Resources Conservation Service), *Robert Coxe* (Delaware Department of Natural Resources and Environmental Control), *Amy Jacobs* (Delaware Department of Natural Resources and Environmental Control), *John Kraeuter* (Rutgers University, Haskins Shellfish Research Lab), *Rick Lathrop* (Rutgers University), *Greg Shriver* (University of Delaware), *Karen Reavy* (Delaware River Basin Commission) and *Bart Wilson* (Delaware Department of Natural Resources and Environmental Control – Coastal Programs) for their invaluable contributions to this project.

PROJECT PARTNERS

The Nature Conservancy, Partnership for the Delaware Estuary and Natural Lands Trust wish to thank the following partner organizations who either provided valuable data or input and/or participated in our two project workshops held on February 23, 2011 at the Delaware River Basin Commission (DRBC) in West Trenton, NJ and May 3, 2011 at the John Heinz Natural Wildlife Refuge (NWR) in Philadelphia, PA. We would also like to think the DRBC and the John Heinz NWR for hosting the project workshops. Inclusion on this list does not indicate endorsement of the final report.

Federal

U.S. Fish and Wildlife Service
- Atlantic Coast Joint Venture
- Delaware Bay Estuary Project

U.S. Army Corp of Engineers - Philadelphia District Office
U.S. Environmental Protection Agency - Region 3
National Oceanic and Atmospheric Administration - Habitat Conservation Division
National Park Service
- Upper Delaware Scenic and Recreational River
- Delaware Water Gap National Recreation Area
- Wild and Scenic Rivers Program

U.S. Geological Survey

Patuxent Wildlife Research Center
U.S. Forest Service
U.S. Department of Agriculture
New Jersey Natural Resource Conservation Service
Delaware Natural Resource Conservation Service

State

New Jersey Department of Environmental Protection
New Jersey Forest Service
New Jersey Fish and Wildlife
Endangered and Nongame Species
Natural Resource Restoration
Office of Natural Lands Management
Delaware Department of Natural Resources and Environmental Control
Delaware Coastal Programs
Delaware Division of Fish and Wildlife
Delaware Natural Heritage Program
Pennsylvania Department of Environmental Protection
Pennsylvania Department of Conservation & Natural Resources
Pennsylvania Fish and Boat Commission
Pennsylvania Natural Heritage Program
Pennsylvania Game Commission
New York Department of Environmental Conservation
New York Natural Heritage Program

Regional

Delaware River Basin Commission
Delaware Valley Regional Planning Commission

Non-Governmental Organizations and Universities

Philadelphia Academy of Natural Sciences
American Littoral Society
American Rivers
Cornell University
Delaware State University
Ducks Unlimited
N.J. Audubon Society
New Jersey Conservation Foundation
Pennsylvania Environmental Council
Philadelphia Water Department
Pinchot Institute
Rutgers University
Haskins Shellfish Research Laboratory
Center for Remote Sensing and Spatial Analysis
Stroud Water Research Center
Trout Unlimited
University of Delaware

HOW TO USE THIS DOCUMENT

The Delaware River Basin Conservation Initiative provides information about the conservation value of the freshwater, estuarine, and bay-related ecosystems and habitat-forming species of the Delaware River Basin. The Introduction of the report reviews the process behind this assessment, followed by sections that provide overviews of the basin's natural features (focusing on the mainstem Delaware River) and the basin's biological resources (highlighting focus species). This is followed by a description of methods used to identify priority areas for each ecosystem and to complete the ecosystem condition assessments. The section entitled "Pulling it all Together" contains the majority of the project results, including sub-basin maps that combine priority areas for each ecosystem and highlight potential conservation strategies for each watershed.

Table of Contents

APPENDICES

(Full appendices document available at http://conserveonline.org/workspaces/nfwfdebasin)

I. Focus Species Profiles
II. Diadromous Fish Habitat Maps
III. Freshwater Ecosystems Measures
IV. Tidal Marsh Ecosystem Measures
V. Benthic Habitat Map of the Delaware Bay
VI. Recommended Conservation Strategies by Watershed (Table)

Executive Summary

The Delaware River Basin Conservation Initiative set out to create a framework for evaluating and prioritizing a discrete set of freshwater, estuarine, and bay-related ecosystems and habitat-forming species of the Delaware River Basin. The goal was to create a biodiversity-driven conservation blueprint for the Basin that would help to ensure a healthy Delaware River and Bay. The creation of this blueprint supports the development of coordinated action and leveraged funding aimed towards a shared set of places where conservation efforts can effectively conserve the Delaware River system.

With funding and guidance from the National Fish and Wildlife Foundation, The Nature Conservancy, Partnership for the Delaware Estuary, and Natural Lands Trust examined a suite of ecosystem and habitat-forming species, including: floodplains, headwaters, non-tidal wetlands, freshwater tidal marsh, brackish and salt marsh, and oysters and ribbed mussels. For each freshwater and tidal marsh ecosystem, we also analyzed factors related to their condition, including aquatic connectivity, flow regime, landscape condition, size, and resiliency.

In brief, the assessment identified conservation priorities for each of the following ecosystems:

- **Floodplain Complexes:** Sixty-Two Floodplain Complexes were identified, where mosaics of floodplain communities across rivers of varying sizes frame the major rivers of the basin.

- **Headwater Stream Networks:** Approximately 49% of the headwaters in the basin were identified as the most physically intact; these headwaters provide intrinsic ecological value while also providing key resources to downstream riverine systems.

- **Non-tidal Wetlands:** Numerous non-tidal wetlands, focusing on those embedded within both headwater and riverine systems, were identified throughout the basin; however, noteworthy concentrations were located in the Glaciated Pocono Plateau and Coastal Plain Provinces.

- **Tidal Marshes:** Due to the ecological importance and significant losses of tidal marsh ecosystems, all freshwater tidal marsh systems over 10 acres (56 identified) and all brackish and salt marsh systems in the Delaware estuary were considered to be priorities, with some of the highest quality habitats located on the Delaware side of the Bay.

- **Oysters and Ribbed Mussels:** The assessment of marine bivalve habitats, specifically oyster reef and ribbed mussel habitats, identified priority areas for both current and future conservation in the Delaware Bay and associated tidal marshes.

Based on these results, we identified and recommended eleven categories of conservation strategies, ranging from forest and shoreline conservation to aquatic connectivity and shellfish restoration. These strategies reflect the diversity of actions – blending protection, restoration, and management – that will be needed to ensure the long-term viability and health of the basin's ecosystems across priority places.

The conservation of these places will require that traditional conservation strategies are coupled with creative, emerging strategies that leverage funding sources and accommodate multiple, and often competing, demands. Opportunities for collaborative conservation efforts are also highlighted in the report. The project results include maps of priority areas and associated conservation strategies.

In addition, we identified and mapped the major **benthic habitat types** of the Delaware Bay using a series of data sources that describe its physical features and biological composition. To arrive at this final map, we mapped the major physical features of the Delaware Bay seafloor, including depth, sediment type, and bottom topography. We then used information on benthic organisms, their distribution and their relationships to these physical features, to delimit a distinct set of environments representing the variety of benthic habitats in the Bay.

Final Products

- Final Maps of Priority Areas and Strategies — Section 5.3
  11x17 maps, organized by sub-basin, illustrate priority areas for each ecosystem
- Recommended Conservation Strategies — Section 5.1
  The maps of priority areas are accompanied by recommended conservation strategies within each watershed. We also highlight some existing programs and funding for these strategies and examples of how agencies and organizations are already collaborating to conserve these ecosystems.
- Delaware Bay Benthic Habitat Maps — Section 4.4
  An ecological marine unit map that maps habitat units based on unique combinations depth, salinity, sediment grain size, and seabed forms, as well as a benthic habitat map the illustrates the combinations of depth, salinity, sediment grain size, and seabed forms that are linked to distinct benthic biological communities.
- Focus Species Profiles — Appendix I
  Profiles developed for 25 Focus Species detail the current status of, threats to, and geographic distribution of species, while also providing potential conservation actions that would benefit these species.
- Accompanying spatial data illustrating priority areas for each ecosystem. — Available on CD from TNC

This work is meant to be a first step in the process of project evaluation, providing a foundation that conservation partners can utilize in a number of ways. The final products can help funders ensure that the projects they support are located in those places where they are mostly likely to have to be the most effective in achieving a conservation impact across the basin. This shared set of conservation priorities also can help provide project applicants seeking funding with an array of places throughout the basin where actions are needed. Additionally, the information contained in these final maps and conservation strategies can be calibrated using local knowledge while also helping local groups to better understand the importance of specific areas within the whole-basin context.

I. INTRODUCTION

The Delaware River Basin is a stronghold of biodiversity along the East Coast of the United States, but it is not without its ecological challenges. The undammed mainstem Delaware River allows numerous species of migratory fish and freshwater mussel species to persist far up into its headwaters where in similar east coast aquatic systems they've been long extirpated. As the drinking water supply for 15 million people, vast areas of the basin's headwaters have been protected from development, providing forested habitat for numerous species as well as protecting headwater streams. In addition, the Delaware Bay provides critical habitat to millions of migratory birds, horseshoe crabs as well as numerous other species. However, since colonial times the basin's resources have been exploited and depleted. By the early 20th century the estuary was considered one of the most polluted waterbodies in the United States and a recurring pollution block in the tidal portion of the lower Delaware impacted diadromous fish runs, which were already severely depleted from overfishing and habitat degradation.

The tide began to turn in the late 1960s. The recognition of the need to conserve the valuable resources of the basin led to the formation of the Delaware River Basin Commission (DRBC) in 1961. Then along came the passage of the Clean Water Act in 1972 which established water quality standards to reduce municipal and industrial discharges, eventually leading to improved water quality and the elimination of the pollution block on the lower river (PFBC 2011). In 1992, DRBC adopted the special protection waters program designed to protect the high water quality of the portions of the river that had been designated as part of the National Wild and Scenic River system. These regulations seek to protect areas where water quality exceeds existing water quality criteria. Through a series of amendments between 1994 and 2008, the special protection waters designation was expanded to apply to point and non-point discharges along the entire mainstem to Trenton, NJ, including all headwaters (DRBC 2011).

Formation of the DRBC represented a landmark step toward improved management of the basin's water resources. Coordination of efforts is as important as awareness of the basin's resources, and the development of documents such as the Water Resources Plan for the Delaware River Basin (2004) helped guide a large number of partners to achieve common objectives. Similarly, the formation of the Partnership for the Delaware Estuary and the development of the Comprehensive Conservation and Management Plan for the Delaware Estuary in 1996 helped focus conservation needs on the heavily-populated estuary. A large array of agencies and organizations continue to work toward protecting and restoring the basin's ecosystems today, guided by a number of additional local, regional, and statewide plans, such as the respective State Wildlife Action Plans (of Delaware, New Jersey, Pennsylvania and New York).

Recognizing the need to build on this existing conservation work to develop a shared set of conservation and restoration priorities for freshwater and estuarine habitats across the basin, the National Fish and Wildlife Foundation (NFWF) provided funding to The Nature Conservancy (TNC), Partnership for the Delaware Estuary (PDE) and Natural Lands Trust (NLT) to create such a product that focused on a basin-wide assessment of riverine and wetland habitats and associated biodiversity. Because so many species utilize discrete habitat types, the project team focused on a suite of freshwater, estuarine, and bay-related ecosystems and habitat-forming species, including headwaters, floodplains, non-tidal wetlands, freshwater tidal marsh, brackish and salt marsh, and oysters and ribbed mussels. We analyzed discrete aspects of their condition and, depending on what condition parameters were degraded or most intact, we then recommended conservation strategies accordingly. In order to have a full picture of the bay ecosystem and its habitats, we also developed a benthic habitat map of the Delaware Bay which we derived from existing datasets describing the biological and physical attributes of the bayfloor.

In addition, we created species profiles for 25 focus species in the basin. Some species are strongly linked to the habitats assessed above, while others, like diadromous fish, depend upon several different habitat types and thus help to link conservation efforts across systems. Profiles include status and extent of the species in the Delaware River Basin, and information on threats, potential conservation actions, and agencies that are responsible for managing the species. These species represent a significant part of the aquatic biodiversity of the basin, and via their associated habitats, can be linked to key areas in need of conservation.

Partner involvement throughout the process helped shape final products. We held two project workshops: the first on methods to identify priority areas and the second on the conservation strategies suggested for priority areas. We also solicited individual partner feedback on project components like data sources used and focus species highlighted.

II. Overview of the Delaware River Basin

Encompassing over 13,000 square miles, most of it forested, the Delaware River Basin contains ecologically significant lands and waters that are important for people and nature. The mainstem Delaware River flows freely for 330 miles from its origin at Hancock, New York, to the Delaware Bay. The mainstem and its major river systems and tributaries support a range of important ecosystems: headwaters, such as those in the Catskills of New York, floodplains, such as those along the Pennsylvania and New Jersey border, non-tidal wetland complexes like those in the Pocono Plateau of Pennsylvania, tidal salt marshes like those fringing Delaware's coast, and marine bivalve habitat like that near New Jersey's shoreline.

According to the most recent State of the Basin report in 2008, approximately 55% of the Delaware River basin is forested, 26% is in agricultural use, and nearly 15% is developed land (DRBC 2008). The upper and central regions are dominated by forest land cover and the lower and bay regions have higher percentages of agricultural, developed, and wetland land cover. The non-tidal reach of the basin's defining feature, the Delaware River, is 197 miles long from head of tide in Trenton, NJ to its headwaters. Downstream of Trenton, the river transitions from predominately freshwater to tidally-influenced to estuarine as it approaches the Delaware Bay.

The Delaware River is the largest river on the Atlantic coast that does not have a dam on its mainstem, allowing unimpeded movement of migratory fishes and other aquatic organisms. Although the river is undammed, river flow is altered by releases from reservoirs on the major tributaries, including the three major New York City water supply reservoirs on the East Branch, West Branch, and Neversink Rivers (PFBC 2011).

Approximately 77% (152 miles) of the non-tidal Delaware River mainstem lies within three areas managed by the National Parks Service: the Upper Delaware Scenic and Recreational River (UDPE); the Delaware Water Gap National Recreation Area (DEWA); and the Lower Delaware National Wild and Scenic River (LODE) (PFBC 2011). Together, these areas provide tremendous opportunities for conservation and recreation along the river corridor.

The DRBC has identified four regions within the basin, with ten separate sub-basins (DRBC 2008) (Figure 2.1):

> The **Upper Region** covers the Delaware River headwaters and contributing watersheds to just below Port Jervis NY. Sub-basins: East and West Branch, Lackawaxen, Neversink and Mongaup.
>
> The **Central Region** is the remaining freshwater river and contributing watersheds between the Upper Region and Trenton NJ. Sub-basins: Upper Central, Lehigh Valley, Lower Central.
>
> The **Lower Region** is the area of tidal flux from Trenton to the head of the bay and all contributing watersheds. Sub-basins: Schuylkill Valley, Upper Estuary, Lower Estuary.
>
> The **Bay Region** includes the Delaware Bay and the surrounding watersheds. Sub-basin: Delaware Bay.

Combined, the Lower and Bay Regions may also be referred to as the Estuary Region; this is the same area that is included in the Delaware Bay National Estuary Program.

The East and West Branches of the Delaware River originate in the forested slopes of the Catskill Mountains. From their confluence, the mainstem Delaware initially flows in a southeasterly direction, forming the boundary between New York and Pennsylvania. The majority of this reach is contained within the Upper Delaware Scenic and Recreational River (UPDE) National Scenic River system maintained by the National Park Service. The topography is characterized by a relatively narrow floodplain as the Delaware River winds through a valley framed by steep mountains. River gradient is high compared to other mainstem reaches. This reach is generally cold, shallow, fast-flowing, and considered to be nutrient-poor (Santoro and Limbeck 2008; PFBC 2011).

At Port Jervis, NY the river flows predominately to the southwest through the Delaware Water Gap toward Easton, PA. The floodplains along this reach tend to be relatively small and confined on the east and west banks by the Kittatinny, Godfrey, and Blue Mountain ridgelines. This reach has slightly higher nutrient concentrations than the upstream reach (Santoro and Limbeck 2008). It is also warmer, with more extensive pools and shorter riffles (PFBC 2011).

The Lehigh River flows into the Delaware River at Easton, PA. From Easton, the Delaware River flows to the southeast toward Trenton, NJ. This reach of the river is a transition zone where both natural and anthropogenic changes to water quality occur. Limestone bands influence the water chemistry of the river and its tributaries. Compared to upstream reaches, this reach has relatively high nutrient concentrations and is warm, with very long pools and fewer riffles; islands are common (Santoro and Limbeck 2008; PFBC 2011). This reach also includes the Lower Delaware National Wild and Scenic area.

The tidal stretch of the Delaware River extends southwest from Trenton, NJ to where the river enters Delaware Bay near Wilmington, Delaware and Salem, NJ. The salt line, where brackish waters meet fresh waters, usually ranges across approximately the lower third of this reach (DRBC 2008). The large tidal variation, wide river width, intensive shipping use, and surrounding urban development all distinguish this river stretch from upstream portions; it has been characterized as the largest freshwater port in the world (Sutton et al. 1996). Freshwater tidal marshes fringing the mainstem and its tributaries provide critical habitat in this stretch. The flat, sandy coastal plain lies from Trenton south and southeast of the fall-line that parallels the Delaware River on the PA side, also giving this area a unique character; most waters have a very low gradient and are warm in temperature.

Where the Delaware River enters the bay, a contiguous band of tidal marshes forms a fringe around the bay's waters, extending to the mouth of the bay at Cape May, NJ and Cape Henlopen, DE. Tidal flow from the Atlantic Ocean and freshwater from the Delaware River and many small rivers and streams are critical to the unique natural landscape of bay. Small rivers and streams that drain directly into the Delaware Bay are all underlain by the Coastal Plain and are typically flat, warm-water streams with marked tidal influence. Although the bay is characterized by extensive tidal marshes, many of them have been historically diked and farmed for salt hay. Other human uses, such as commercial fishing, sand mining, and agriculture, have played a role in molding the landscape of the Bay.

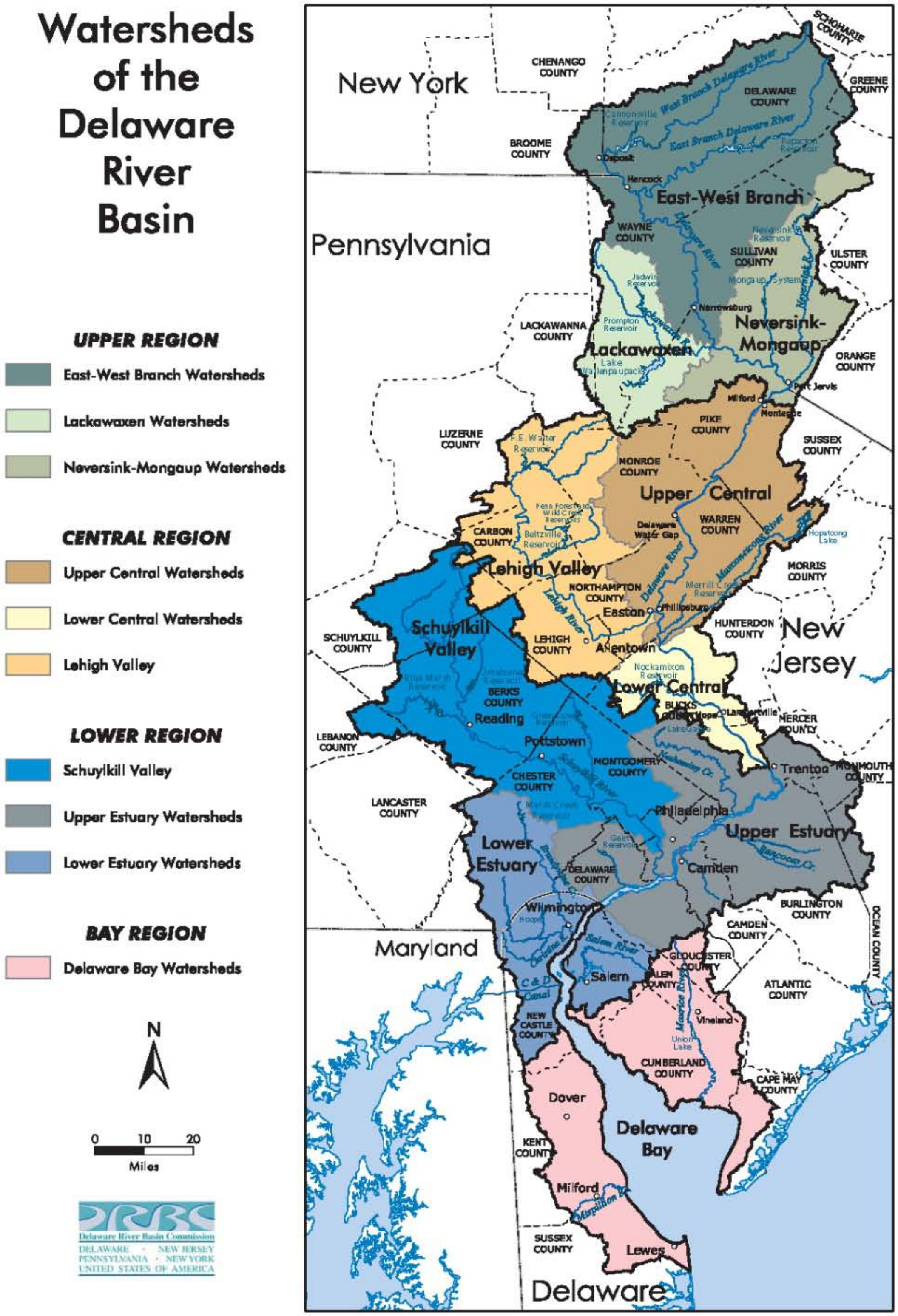


Figure 2.1. Delaware River Sub-Basins (Source: DRBC)

III. Biodiversity of the Basin

Hundreds of species thrive in the variety of stream, wetland, floodplain, and tidally-influenced habitats of the Delaware River Basin. In this section, we present an overview of biological diversity within some of the major taxonomic groups in the basin: fish, reptiles and amphibians, freshwater mussels, estuarine invertebrates, birds, mammals, and riverine and estuarine vegetation. Within each major taxon, we group species that share a common life history strategy, home range, habitat niche, or other trait – for example, cool-cold headwater fishes or colonial nesting and wading birds. We also note how these species are likely to be associated with various basin habitats that are included in our ecosystem assessments.

We also provide more detailed information for a limited number of fish and wildlife species within the basin. These "**focus species**" were selected for their rarity, status, and/or functional, economic, or iconic importance in the basin. It is not an exhaustive list and many deserving species are not included. Most of these species are identified as Species of Greatest Conservation Need in state wildlife action plans in one or more basin states. For each focus species, we completed a species profile that highlights the agency(s) responsible for the species, status and extent of the species in the Delaware River Basin, threats, and potential conservation actions. These profiles can be found in Appendix I. By highlighting basin-specific status and conservation-related issues, the profiles are intended to complement the general overviews on species biology that are readily available online and in other formats. In our sub-basin summaries provided with the priority conservation area maps in Section V, we also highlight specific places within the basin where species-focused conservation is most needed or most relevant, given species range, habitat use, or ecological conditions. Throughout this section, **focus species** are emphasized in bold.

3.1 Fish

Records estimate that more than 90 fish species spend some portion of their life within freshwater and tidal rivers and wetlands of the Delaware River (Cooper 1983). NOAA (2011) estimates that 130 fish use estuarine habitats of the basin and bay. Minnow (Cyprinidae) and sunfish (Centrarchidae) families account for almost half of the basin's fish diversity (Cooper 1983). Five species may be extirpated: pirate perch (*Aphredoderus sayanus*), mud sunfish (*Acantharchus pomotis*), blackbanded sunfish (*Enneacanthus chaetodon*), swamp darter (*Etheostoma fusiforme*), and longnose gar (*Lepisosteus osseus*) (Cooper 1983; Horwitz et al. 2008).

Cool-cold Headwater Species: These species occur in headwaters and small streams that have a cold-cool temperature regime, low turbidity, and moderate to swift currents. They may also use headwater wetlands during particular life stages. **Brook trout** (*Salvelinus fontinalis*) is the basin's only native salmonid. This species requires coarse substrates and high intergravel dissolved oxygen (DO) for successful egg and larval development. Juveniles develop in channel margins and shallows of headwater streams and wetlands. Juvenile and adult growth is largely influenced by baseflow conditions, which affect stream depth, velocity, wetted width, and temperature (Denslinger et al. 1998; Hakala and Hartman 2004). Turbidity also influences egg and larval development and juvenile and adult feeding habits (Denslinger et al. 1998; Hudy et al. 2005). Brook trout populations have been severely reduced, both locally and regionally, due to land cover change and associated changes in water quality, fragmentation by dams and roads, habitat destruction, introduction of nonnative salmonids, and modification of temperature regimes from reservoir releases (Hudy et al. 2005; Horwitz et al. 2008). Sculpin (Cottidae) often co-occur with brook trout but may tolerate slightly warmer stream temperatures. Both slimy and mottled sculpin occur in the basin and have been documented as potential host fish for several mussel species, including dwarf wedgemussel (*Alasmidonta heterodon*), brook floater (*Alasmidonta varicosa*), and creeper (*Strophitus undulatus*) (Nedeau et al. 2000; CTDEP 2003). Brook trout and sculpin have small home ranges and need networks of connected headwaters and small streams to maintain genetic diversity and minimize the risk of localized extinction (Letcher et al. 2007).

Transitional Cool and Warm Backwater Species: These species thrive in cool or warm sluggish headwater streams and in backwaters of small and large rivers. **Bridle shiner** (*Notropis bifrenatus*) were once abundant in Delaware Basin (historically found in 13 counties) but now are considered rare. Declines have been rapid and range-wide over the past 50 years (Cooper 1983; PNHP 2010). Recent surveys within the basin have documented bridle shiners in small sluggish warm-water creeks, permanent backwaters within the floodplain, and in beaver ponds. They were often found swimming above and into patches of submerged aquatic vegetation, which are used for cover and during spawning (Horwitz et al. 2008). While they were never abundant, ironcolor shiner (*Notropis chalybaeus*) distributions have also decreased. Only two populations have been documented recently in the basin (Lellis and Johnson 2006; NYDEC 2011). Both shiners spawn over aquatic vegetation (Jenkins and Burkhead 1993). Possible causes of species decline include siltation, loss of aquatic vegetation, and a reduction in critical backwater habitat historically created by beavers (Horwitz et al. 2008; PNHP 2010). Bluespotted sunfish (*Enneacanthus gloriosus*), eastern mudminnow (*Umbra pygmaea*), and redfin pickerel (*Esox americanus*) also thrive in vegetated backwater pools and wetlands within the floodplain of major tributaries and the mainstem river (Horwitz et al. 2008). Adjacent land cover, lateral connectivity, and groundwater contribution are important to maintaining vegetation, temperature, and dissolved oxygen in these habitats.

Riffle Obligates and Associates: These species either spend most life stages in riffle habitats or require access to riffle habitats during spawning. They use riffles in a variety of basin stream and river types, from steep headwaters to large rivers, and in cold, cool, and warm thermal regimes. Longnose dace (*Rhinichthys cataractae*), margined madtom (*Noturus insignis*), and central stoneroller *(Campostoma anomalum*) are considered riffle obligates, preferring moderate to fast currents over sand and gravel substrates. They are important indicators of the persistence of shallow, fast water habitats and serve as host fish for several freshwater mussel species. The northern hogsucker (*Hypentelium nigricans*) and the less common longnose sucker (*Catostomus catostomus*) require access to riffle habitats during spawning. During spring and early summer, suckers migrate from the basin's mainstem and major tributaries to spawn in small streams and headwaters. This life history strategy requires long, longitudinally-connected stream networks. Greeley (1936) documented longnose sucker in the headwaters and mainstem of the West and East Branch; however, construction of the Cannonsville and

Pepacton Reservoirs disconnected spawning habitat. No recent occurrences have been documented on the East and West Branch downstream of the reservoirs (Horwitz et al. 2008). Isolated populations may occur upstream.

Nest Builders: Fallfish (*Semotilus corporalis*), creek chub (*Semotilus atromaculatus*), river chub (*Nocomis micropogon*), and redbreast sunfish (*Lepomis auritus*) can be found throughout the basin and share a hydraulically-sensitive spawning habit: they build nests in riffles, pools, and/or channel margins. Their nests are concurrently or subsequently used by dozens of species for egg and larval development (Sabaj et al. 2000). Fallfish also serves as a host fish for freshwater mussels (Strayer and Jirka 1997; CTDEP 2003). Nest builders require maintenance of suitable nesting substrate and are sensitive to extreme high and low flow events that could flush or desiccate eggs, respectively. Changes to land cover, loss of baseflows, and high flow events during spawning could impact nesting success.

Diadromous Species: The basin is home to ten diadromous fish species that migrate between freshwater and marine habitats during their life cycles (Cooper 1983; Greene et al. 2009; NOAA 2011). Anadromous fish, including clupeids (**American shad**, *Alosa sapidissima*; hickory shad, *A. mediocris*; **alewife**, *A. pseudoharengus*; and **blueback herring**, *A. aestivalis*), **Atlantic sturgeon** (*Acipenser oxyrinchus*), sea lamprey (*Petromyzon marinus*), striped bass (*Morone saxatilis*), and rainbow smelt (*Osmerus mordax mordax*) spend most of their lives at sea before returning to natal rivers to spawn. Catadromous species, specifically American eel (*Anguilla rostrata*), migrate from the ocean into freshwater environments as juveniles. Once mature, they emigrate to spawn in marine environments. Although often referred to as an anadromous species, **shortnose sturgeon** (*Acipenser brevirostrum*) in the Delaware River are more correctly referred to as an amphidromous species, as they move between freshwater and the bay to feed, but not to spawn. See page 9 for more information about the importance of the Delaware River for diadromous fish populations.

All of these life strategies require longitudinal connectivity between marine and freshwater environments. The Delaware River is unique among major eastern rivers, in that its mainstem is free of any dams, allowing these species to access much of their historic habitat. However, overfishing, pollution, and barriers on tributaries have negatively affected diadromous fish populations in the basin, with most populations currently at historic lows (ASMFC 2006; ASMFC 2007).

Saline Generalists: The mummichog (*Fundulus heteroclitus*) is a common fish distributed widely in coastal waters and salt marshes. Mummichogs breed in salt marshes, where they frequently feed on mosquito larvae. The banded killifish (*Fundulus diaphanous*) and eastern silvery minnow (*Hybognathus regius*) are other common nearshore fish that comprise an important part of the diet of many of the larger commercially important fish in the bay.

Estuarine and Coastal Obligates: Atlantic menhaden (*Brevoortia tyrannus*) are an important component of the marine ecosystem, serving as a food resource for many species of predatory fish. Bay anchovy *(Anchoa mitchilli)*, Atlantic silverside (*Menidia menidia)*, and striped killifish (*Fundulus majalis*) are other small fish species that are widespread and abundant in nearshore and tidal marsh areas.

Diadromous Fish & the Delaware River ~

The Delaware River is unique – all other major rivers on the East Coast of the United States have been dammed along their mainstems, blocking passage of migratory and even resident fish, but the Delaware River is undammed along its mainstem, making it the longest undammed river east of the Mississippi. Among the many species that make the Delaware Basin special, perhaps no group of species is more closely linked to our history than diadromous fish, in part because the Delaware is still free-flowing. Charles Harding III (1999) details the history of the Delaware Basin from the 1600s from the perspective of the American shad, a history of the overexploitation of a once incredibly abundant species. Although there is debate as to whether American shad actually saved Washington's starving troops on the Schuylkill, the importance of this fish to the Delaware Basin is undisputed. W.E. Meehan, the Commissioner of Fisheries of PA, nicely illustrated how important shad were to the people living in the Delaware Basin at the turn of the 19th century:

"There is little that people living along the line of the Delaware valley are more interested in or guard more jealously than the shad industry in the Delaware River. From the lowermost point of Delaware Bay to the shallows of the river in New York state, the people look forward to and seek with great eagerness the delicious shad as they ascend in the spring to spawn. In comparison with this magnificent food fish any other industry sinks into significance in the minds of the men and women who are within reach of the supply. If any man in his own financial interest talks of constructing a dam, however small, across the river, there is an uproar raised about the matter at once." W. E. MEEHAN, Commissioner of Fisheries of Pennsylvania. 1907.

Unfortunately, both the extremely lucrative shad fishery and the sturgeon fishery had collapsed by the early 1900s. Today shad and river herring are at historical lows in abundance, Atlantic sturgeon has been recommended for Endangered Species Act (ESA) listing, and American eel is once again under consideration for ESA listing. The story is much the same on other major rivers along the Atlantic coastline, but on the Delaware, the lack of mainstem dams and intact headwater condition holds the potential for a full recovery of most diadromous species. Recovery is possible with focused protection and restoration efforts on our tributaries that are still dammed, protection of critical in-stream sturgeon habitats, and better fisheries management. We mapped spawning runs for shad, river herring, and sturgeon, as well as critical habitats for Atlantic sturgeon and shortnose sturgeon using available literature and data from tracking research to highlight potential places for restoration and protection. These maps can be found in Appendix II.

The Delaware Bay is an important spawning area for weakfish (*Cynoscion regalis)*; this species' population is currently very low compared with historic estimates of abundance. Black drum (*Pogonias cromis)* and white perch (*Morone americana)* also use the bay for spawning, and juveniles use tidal creeks as nursery areas.

Several flatfish are common in bay waters, including summer flounder (*Paralichthys dentatus)*, winter flounder (*Pseudopleuronectes americanus)*, hogchoker (*Trinectes maculates)*, and windowpane flounder (*Scophthalmus aquosus)*. Several shark species are also closely associated with the bay and are of increasing conservation concern, including the sandbar shark (*Carcharhinus plumbeus)* and the sandtiger shark (*Carcharias taurus),* along with smooth (*Mustelus canis)* and spiny dogfish (*Squalus acanthias)*.

3.2 Reptiles and Amphibians

Dozens of species of reptiles and amphibians can be found throughout the basin in headwater, wetland, floodplain, and tidal marsh habitats. Because their life cycles require connectivity among suitable hibernation, breeding, and nesting habitats, they are sensitive to land cover change and proximity to roads (Calhoun and deMaynadier 2008). Many species within this group hibernate in stream banks, stream beds, or wetland beds from fall to early spring. During hibernation, they require baseflow and hydrologic conditions that buffer freezing temperatures and supply oxygen (Hulse et al. 2000).

Aquatic Lotic Species: Highly adapted to flowing water habitats, these species can be found throughout the basin from headwater streams to the mainstem. Lungless salamanders (Plethodontidae) are most abundant in and along headwater and small stream systems. This group includes dusky (*Desmognathus* spp.), brook (*Eurycea* spp.), spring (*Gyrinophilus* spp.), and red and mud (*Pseudotriton* spp.) salamanders. They are particularly sensitive to changes in groundwater, surface hydrology, and water temperature. These changes affect egg and larval development and the efficiency of gas exchange through their skin (Rocco and Brooks 2000; Moore and Sievert 2001). The queen snake (*Regina septemvittata*), found in moderate to fast-flowing small streams and rivers, feeds almost exclusively on crayfish (Hulse et al. 2000). Northern map turtle (*Graptemys geographica*) and common musk turtle (*Sternotherus odoratus*) spend both juvenile and adult stages in large river habitats. During the nesting season, adults can migrate more than one kilometer in search of suitable habitat on islands and within the floodplain (Richards and Seigel 2009).

Semi-aquatic Lotic Species: These species rely on flowing waters or habitats within the active channel for at least one life stage, but spend part of their life cycle in floodplain or upland environments. **Bog turtles** (*Glyptemys muhlenbergii*), wood turtles (*Glyptemys insculpta*), and spotted turtles (*Clemmys guttata*) occur in headwater and small stream habitats. Bog turtles are extreme habitat specialists found in spring-fed wetlands, small open streams, and seepages that support hydrophytic vegetation (Hulse et al. 2000). With a small home range and narrow habitat requirements, bog turtle individuals and populations are vulnerable to changes in land cover or ground and surface water hydrology. Wood turtles travel and nest within riparian areas associated with brook trout streams, but they use the active channel during hibernation and as a migration corridor during extremely cold periods or during drought.

Northern leopard frogs (*Rana pipiens*) can be found along vegetated margins of slow-flowing small streams and rivers.

Floodplain and Vernal Species: These species reside outside of the active channel in floodplain and/or upland vernal habitats and are dependent on connectivity among groundwater, the river, and its floodplain to maintain sediment, vegetation, and moisture regimes. They include mole salamanders (Jefferson salamander, *Ambystoma jeffersonianum*; spotted salamander, *A. maculatum*; blue-spotted salamander, *A. laterale*; eastern tiger salamander, *A. tigrinum*; and marbled salamander, *A. opacum*), which migrate to vernal pools for breeding. Mole salamanders depend on specific water temperatures and hydroperiods to support egg and larval development (Conant and Collins 1998). Similarly, the eastern spadefoot (*Scaphiopus holbrookii*) primarily uses vernal habitats for breeding. Within the floodplain they can be found in open, low-lying areas in well-drained, sandy to gravelly soils. The eastern hognose snake (*Heterodon platirhinos*) also prefers sandy substrates and is associated with rivers and floodplains of the Ridge and Valley province (Hulse et al. 2000). Blanding's turtle (*Emydoidea blandingii*) is very rare, occurring only in the upper basin in shallow, vegetated wetlands and ponds, and occasionally the main channel (NYDEC 2010).

Tidal Marsh and Coastal Species: Sea turtles, primarily loggerhead (*Caretta caretta)* and Kemp's Ridley (*Lepidochelys kempii)*, occur in the Delaware Bay during summer months. The **diamond-backed terrapin** (*Malaclemys terrapin)*, an estuary-obligate species, spends its life in tidal marshes and nearshore waters and breeds on sandy beaches and other adjacent uplands fringing the bay's wetlands.

3.3 Freshwater Mussels

As some of the least mobile and longest-living aquatic organisms in the basin, mussels provide a lens to evaluate long-term trends and conditions (Grabarkiewicz and Davis 2008). As filter-feeding bivalves, they are important links in the food chain, filtering bacteria and suspended materials from the water. Their reproduction is complex, relying on species-specific host fish for successful rearing of larval glochidia. At least a dozen species are native to the basin, most of which occur in the upper basin and have experienced a significant reduction in distribution and abundance (PFBC 2011).

Primarily Riverine Species: A few of the basin's freshwater mussel species are closely associated with riverine habitats, including **brook floater** (*Alasmidonta varicosa*), **green floater** (*Lasmigona subviridis*), **dwarf wedgemussel** (*Alasmidonta heterodon*), and creeper (*Strophitus undulatus*). These four species are long-term brooders, requiring suitable spawning conditions in the summer and fall, and access to host fish in the spring and early summer. Host fish include darter, sculpin, and minnows. Green floater is commonly found in streams with stable baseflow and good water quality (Grabarkiewicz and Davis 2008; R. Villella, personal communication 2009). In the basin, dwarf wedgemussel occurs in small rivers, major tributaries, and on the mainstem near islands on low gradient reaches (Cole et al. 2008). Eastern pearlshell (*Margaritifera margaritifera*) is a long-lived, short-term brooder, spawning and releasing glochidia in the same season. They may live more than 100 years, making it the longest-lived invertebrate known on the planet. They require high quality cool-cold water streams, and use brook trout as a host fish. Their populations have become very isolated due to the presence of roads and dams that limit colonization (Nedeau et al. 2000).

Semi-riverine Species: These species include **alewife floater** (*Anodonta implicata*), triangle floater (*Alasmidonta undulata*), **yellow lampmussel** (*Lampsilis cariosa*), and Eastern elliptio (*Elliptio complanata*). They are found in a variety of basin habitats, including small streams, large rivers, and lakes. Yellow lampmussel and eastern elliptio are associated with larger-bodied, mobile host fish. Alewife floater is also associated with highly mobile host fish, possibly including American shad and blueback herring, in addition to alewife (Nedeau et al. 2000). Because their host fish are highly mobile, species recruitment is directly related to longitudinal connectivity. Alewife floater populations expanded in direct response to the installation of fish passage (Smith 1985).

3.4 Other Estuarine Invertebrates

Horseshoe crabs *(Limulus polyphemus)* concentrate in the Delaware Bay to spawn on the sandy beaches fringing its shorelines. The vast quantities of eggs the crabs deposit on these beaches serve as an important food resource for migrating shorebirds. **Blue crabs** (*Callinectes sapidus*) are a ubiquitous, commercially-important species found throughout the waters of the estuary. Oysters *(Crassostrea virginica*) play an important role in the bay, as oyster reefs provide essential habitat for numerous other estuarine species and protect shorelines from erosion. The basin-wide filtration capacity of ribbed mussels *(Geukensia demissa)* has been estimated to exceed that of oysters and other native bivalves and it also plays a foundational role in the ecology of its primary habitat, salt marshes. The waste produced by ribbed mussels helps these marshes build elevation, and the presence of mussels also helps marshes resist erosion. (More information on oysters and ribbed mussels can be found in Section 4.3, the Marine Bivalve Habitat Ecosystem Assessment).

3.5 Birds

As part of the Atlantic flyway, the habitats of the Delaware Basin are used by hundreds of resident and migratory bird species for feeding, nesting, and/or breeding (USNPS 1997). Major groups of birds include colonial nesting and wading birds, fish-eating raptors, and riparian and wetland breeders. Species within these groups are sensitive to land cover condition, habitat availability, food abundance, and water quality.

Fish-eating Raptors: Both the **bald eagle** (*Haliaeetus leucocephalus*) and osprey (*Pandion haliaetus*) prey primarily on fish; both species nest in large trees or platforms in the floodplain of major tributaries and the mainstem. The Delaware River from Hancock, NY to the Delaware Water Gap is one of the largest and most important inland bald eagle wintering habitats in the northeastern United States (USGS 2003; DRBC 2011a). The Delaware River is considered an "essential" bald eagle winter habitat, as specified by the Northern States Bald Eagle Recovery Plan (USFWS 1983). Bald eagles and ospreys use the Delaware mainstem and bay shores extensively during migratory stopovers and, more recently, as breeding habitat (USNPS 1997).

Riparian and Wetland Breeders: Several species use the basin's riparian corridors and/or wetlands for breeding habitat. American woodcock (*Scolopax minor*), belted kingfisher (*Megaceryle alcyon*), **Louisiana waterthrush** (*Parkesia motacilla*), winter wren (*Troglodytes hiemalis*), yellow-breasted chat (*Icteria virens*), and several species of flycatchers, warblers, and vireos all have some association with riparian or wetland habitats. Of these species, the **cerulean warbler** (*Dendroica cerulea*), Acadian flycatcher (*Empidonax virescens*), and Louisiana waterthrush appear to be most consistently and significantly associated with high-quality, forested riparian or wetland habitats, particularly during the breeding season. The cerulean warbler, which has declined across its range, has the most limited geographic distribution of the three. It shows an affinity for riparian and bottomland habitats with a tall mature tree canopy. The Acadian flycatcher, found throughout the basin, prefers lowland areas in old-growth woodlands near streams and narrow, hemlock-lined ravines in the northern portion of the basin. The Louisiana waterthrush occurs almost exclusively along the narrow riparian corridors of headwater streams (Brauning 1992; PGC and PFBC 2005).

A number of species, including the prothonotary warbler (*Protonotaria citrea*), the red-shouldered hawk (*Buteo jamaicensis*), the yellow-bellied flycatcher (*Empidonax flaviventris*), and the marsh wren (*Cistothorus palustris*), are area-sensitive, requiring large wetland habitats in a high-quality landscape context. The prothonotary warbler has been associated with extensive wooded swamps greater than 247 acres (PGC and PFBC 2005). The red-shouldered hawk requires large forested patches with wet openings. The yellow-bellied flycatcher requires large blocks of palustrine wetlands. The marsh wren has been found to be associated with tidal marshes greater than 20 acres (Brauning 1992; PGC and PFBC 2005).

Colonial Nesting and Wading Birds: Several species, including black-crowned night heron (*Nycticorax nycticorax*), great blue heron (*Ardea herodias*), tricolored heron (*Egretta tricolor)*, little blue heron (*Egretta caerulea)*, great egret (*Casmerodius albus*), snowy egret (*Egretta thula*), yellow-crowned night heron (*Nyctanassa violacea*) and glossy ibis (*Plegadis falcinellus*) use a wide range of aquatic habitats, including lakes, wetlands, tidal marshes, and slow-moving reaches of large rivers. These species nest in colonies in forested floodplains, estuaries, and on islands. They hunt for prey by wading along the water's margins. Nest sites are sensitive to disturbance, and populations are sensitive to water quality and prey availability (PGC and PFBC 2005). The most common and largest of these species, the great blue heron, has rookeries throughout the basin, from the tidal reaches of the mainstem to the floodplains along the Upper Delaware. The great egret and the black-crowned night heron are most commonly associated in the southern and tidal portion of the basin (Brauning 1992). The largest heron rookery in the mid-Atlantic, with over 6,000 pairs of nesting birds, is within Supawna Meadows National Wildlife Refuge, specifically Pea Patch Island (USFWS 2010).

Shorebirds: The marshes and shorelines of Delaware Bay provide critical stopover habitat for numerous species of shorebirds on their north- and south-bound migrations. These include sanderling (*Calidris alba)*, ruddy turnstone (*Arenaria interpres)*, **red knot** (*Calidris canutus rufus)*, semipalmated sandpiper (*Calidris pusilla)*, black-bellied plover (*Pluvialis squatarola*), short-billed dowitcher (*Limnodromus griseus*), and dunlin (*Calidris alpine*). During their north-bound migration in spring, several of these species use the bay specifically to feed on horseshoe crab eggs.

Tidal Marsh Obligates: Several species breed almost exclusively in salt marshes. These include black rail (*Laterallus jamaicensis*), clapper rail (*Rallus longirostris*), eastern willet (*Tringa semipalmata semipalmata*), seaside sparrow (*Ammodramus maritimus*), **salt marsh sparrow** (*Ammodramus caudacutus*), and coastal plain swamp sparrow (*Melospiza georgiana nigrescens*).

Waterfowl: The Delaware Bay hosts one of the largest concentrations of wintering **black duck** (*Anas rubripes*) on the East Coast. The marshes and coastal waters provide stopover and wintering habitat for many other species of waterfowl as well, including snow goose (*Chen caerulescens*), northern pintail (*Anas acuta*), and green-winged teal (*Anas carolinensis*). At different times of year, the open waters of the bay host large numbers of sea ducks, loons, and northern gannet (*Morus bassanus*).

3.6 Mammals

Both the northern river otter (*Lontra canadensis*) and the **North American beaver** (*Castor canadensis*) are strongly associated with riverine environments. The otter inhabits lakes, rivers, streams, bays, estuaries, and associated riparian habitats, making their dens in the banks of streams and rivers. They primarily feed on non-game fish (minnows, carp, and suckers) and crayfish. The beaver, the largest rodent in North America, is a dynamic engineer that creates many wetland/stream complexes and is essential to the maintenance of a shifting mosaic of wetlands, marshes, floodplains, and streams (Merritt 1987). Both species are currently enjoying resurgences due to decreased trapping pressure for the beaver, and a ban on trapping coupled with reintroduction programs for the river otter.

3.7 Non-tidal Riverine and Floodplain Vegetation

Within the Delaware River Basin, several assessments have been completed which identify more than a dozen riverine and floodplain vegetation communities that can be organized into four major vegetation groups based on vertical zonation and dominant disturbance regimes: submerged and emergent bed, herbaceous, scrub-shrub, and floodplain forest (Fike 1999; Eichelberger et al. 2009; Fanok et al. 2009). The disturbance regimes associated with this vegetation gradient sustain the diverse structure and associated niche habitats critical to the conservation of many of the basin's native species, including colonial nesting birds, yellow-throated and warbling vireo, cerulean warbler, Louisiana waterthrush, Acadian flycatcher, bald eagle, red-shouldered hawk, adult turtles and hatchlings, eastern ribbon snake, mink, and river otter (PGC and PFBC 2005).

Submerged Aquatic Vegetation and Emergent Beds: Submerged aquatic vegetation (SAV) is found in streams and rivers throughout the basin in portions of the active channel that are permanently inundated during the growing season. SAV is a key primary producer, providing substrate for epiphytic algae, physical structure, cover, and low-velocity refuges. Presence of SAV has been linked to increased macroinvertebrate abundance, and it provides critical habitat for fish, such as juvenile alosids and adult silver eels (Hutchens et al. 2004). *Podostemum ceratophyllum*, or riverweed, is a SAV species highly sensitive to changes in turbidity, dissolved oxygen, and hydrology (Munch 1993). It occurs in moderate- to fast-flowing reaches of small streams and major tributaries. Emergent aquatic vegetation also is found in streams and rivers throughout the basin, typically within portions of the active river channel with semi-permanent inundation, such as island heads, edges of bars, channels, and terraces. One example, water willow (*Justicia americana*), relies heavily upon severe ice and flood scour to promote regeneration, as well as light conditions and maintenance of baseflows to avoid desiccation (Strakosh et al. 2005).

Wild celery is a characteristic submerged aquatic plant of the freshwater tidal portion of the river (*Vallisneria americana*). Eelgrass (*Zostera marin*a) is a characteristic species of higher salinity tidal areas, although this species is not commonly found in the bay, and its historic distribution there is unclear. Both species provide habitat and food for a variety of estuarine fish, invertebrates, and birds.

Herbaceous Communities: Herbaceous communities occur in areas that have undeveloped soils and may be subject to seasonal flooding. Big bluestem (*Andropogon gerardii*) occurs along shorelines and islands in the Delaware River on sand and gravel in droughty locations; it can support rare woody species including sand cherry (*Prunus pumila*) (Eichelberger et al. 2009). Large, high-quality examples of this community type are rare. Hairy-fruit sedge wetland is associated with mainstem islands, floodplains, and backwater sloughs of major tributaries where canopy cover is absent. The community relies on flood regime and inundation to maintain this serial state. Examples of calcareous riverside seeps are rare, occurring in only a handful of locations in the basin where natural seepage flows over cobbled limestone, and serial stage is maintained by ice scour. Calcareous riverside seeps often have many rare plants within them.

Scrub-shrub: Typically occurring as a transition community between herbaceous and forest states, scrub-shrub structure is maintained by a balance of inundation frequency and duration and moderate to severe flood and ice sour. Communities include sycamore-mixed hardwood (willow), riverine and dwarf shrublands, and buttonbush wetland. Structural diversity provided by this community is particularly important cover for birds, mammals, reptiles, and amphibians (PGC and PFBC 2005).

Riparian and Floodplain Forest: Dominant riparian and floodplain forest communities include eastern hemlock, red maple-willow, sycamore, bitternut hickory lowland forest, river birch low floodplain forest, silver maple floodplain forest, and sugar maple floodplain forest (Eichelberger et al. 2009; Fanok et al. 2009). While these communities occur along a variety of stream sizes and occupy different positions within the floodplain, they all rely on stream and groundwater hydrology to maintain suitable conditions for seed dispersal and establishment and to reduce competition with upland species (Burns and Honkala 1990; Zimmerman 2006).

3.8 Palustrine Wetlands

Palustrine wetlands are non-tidal wetlands that occur outside of the active stream channel, lack flowing water, and are dominated by trees, shrubs, and/or persistent emergents (Cowardin et al. 1979). The basin's palustrine wetland communities include acidic seepage swamps, calcareous wetlands (seepage swamps and fens), and vernal pools. Occurring throughout the basin, acidic seepage swamps support a variety of species, including cranberry (*Vaccinium macrocarpon*), bog laurel (*Kalmia polifolia*), boreal conifers such as black spruce (*Picea mariana*), and larch (*Latrix laricina*), Atlantic white cedar (*Chamaecyparis thyoides*), and swamp pink (*Hellonius bulata*) (Davis 1993; USFWS 2011). Calcareous seepage swamps occur in the upper and mid-basin and are typically dominated by woody species such as red maple (*Acer rubrum*), black ash (*Fraxinus nigra*), and spice bush (*Lindera benzoin*). Very rare wetland obligate plant species occur in this habitat, including the spreading globeflower (*Trollius laxus*) and showy lady's slipper (*Cypripedium reginae*) (Davis 1993). Calcareous fens also have rare endemic associates. Because of their small size, land use change and groundwater withdrawals can severely degrade calcareous fens (Davis 1993). Vernal pools occur in a diversity of basin settings from headwater seepages to depressions embedded within large river floodplains. Several species' life cycles are dependent on the seasonal wetting and drying and fishless waters that vernal pools provide (Calhoun and deMaynadier 2008). These systems are highly impacted by direct and indirect changes to local hydrology, including groundwater extraction and land use change (Calhoun and deMaynadier 2008).

3.9 Tidal Marsh Aquatic Vegetation

The plants of tidal marshes are adapted to dynamic flooding regimes and specific salinity conditions. Freshwater, brackish, and saltwater tidal marshes each have a suite of specialized plant species. These plant communities are limited in extent, occupying a narrow range along coastal fringes and streams. Freshwater tidal and brackish plant communities are the most limited in extent, in part because dams and development have interrupted the natural gradient between fresh and salt water in estuarine watersheds.

Freshwater Tidal Wetlands: Freshwater tidal wetlands occur in the upper reaches of small coastal rivers and are extensive along the Delaware River at the upstream end of the estuary. Characteristic plants of this habitat include arrowhead (*Sagittaria* spp. *)*, pickerelweed (*Pontederia cordata)*, arrow arum (*Peltandra virginica)*, and wild rice (*Zizania aquatica)*. Wild rice in particular is known to attract large numbers of rail and waterfowl to this habitat.

Saltwater Marsh: Salt marshes, characterized by a low diversity of salt-adapted plants, are a mosaic of tidal creeks, pools, and shallow vegetation-free pannes. Salt marsh can be divided into high and low marsh, each of which has characteristic plant species. Low marsh is composed of a single species, smooth cordgrass (*Spartina alterniflora)*. High marsh is primarily composed of saltmeadow cordgrass (*Spartina patens*,) along with spike grass (*Distichlis spicata*), glassworts (*Salicornia* spp.), and marsh lavender (*Limonium carolinianum).*

Brackish Marsh: At the transition between freshwater and saltwater tidal marshes is a brackish gradient. These marshes have many of the salt marsh plant species along with additional species such as big cordgrass (*Spartina cynursoides)*, bulrushes (*Scirpus* spp.*)*, Catails, (*Typha* spp.*)*, salt marsh fleabane (*Pluchea odorata*), and swamp rose mallow (*Hibiscus moscheutos*). An invasive non-native variety of the common red (*Phragmites australis spp.)* , has come to dominate the vegetation community in some brackish marsh areas.

Marsh Upland Ecotone: The ecotone between tidal marshes and upland forests is also characterized by a unique plant community adapted to coastal conditions. This transition zone is often shrub-dominated, with bayberry (*Myrica pennsylvanica*), groundsel tree (*Baccharis halimifolia*), and marsh elder (*Iva annua)* as the characteristic species. This zone has also come to be dominated by the common reed (*Phragmites australis)* in many places.

IV. Ecosystem Condition Assessments

In order to identify the places within the basin where conservation efforts could most effectively protect and restore aquatic biodiversity, we focused our assessment on representative freshwater and estuarine ecosystems. Focusing on a short list of ecosystem types enabled us to use measures related to ecosystem functions and habitat condition for associated species without having to analyze separately every habitat type and species found in the basin.

Our representative freshwater ecosystem types are **floodplains, headwaters,** and **non-tidal wetlands**. Our estuarine ecosystem types are **tidal freshwater, brackish and salt marshes** that fringe the Delaware Bay. Because of their importance as habitat-forming species, we also included two **marine bivalve** species, specifically Eastern oysters, a reef forming bivalve, and ribbed mussels, which aid in marsh stabilization. This section outlines the ecological importance of these important basin ecosystems, how we identified priority conservation areas, and how we assessed their respective conditions based on various ecological measures.

4.1 Freshwater Ecosystems – Floodplains, Headwaters and Non-Tidal Wetlands

4.1.1 Floodplains

Ecological Importance

Floodplains are key components of freshwater systems. Within these dynamic environments, the interaction of factors such as climate, hydrology, sediment regime, and geomorphology creates a mosaic of habitats that shifts through time and space. The functional benefits and habitat diversity of floodplains have few parallels in other ecosystems (Naiman and Décamps 1997). Providing the geomorphic setting for floodplain forests, ice-scour grasslands, and mixed-hardwood shrublands, these systems help to regulate light, temperature, nutrient, sediment, and flow regimes of adjacent rivers, while also supporting broad-based food webs that help sustain a diverse assemblage of fish and wildlife (Committee on Riparian Zone Functioning and Strategies for Management 2002).

At the interface between terrestrial and aquatic systems, floodplains provide a lateral ecotone between land and water, forming a complex gradient between the river channel and nearby uplands. Floodplains include semi-permanently to seasonally flooded vegetation of the riverbed, banks, and islands, as well as temporarily flooded and saturated floodplain communities. This landscape is shaped by the severity and frequency of flooding, ice scour, direction of flow, and differences in substrate.

Longitudinally, floodplains frame our waterways and enable species dispersal along the riverine corridor. They also provide a vertical ecotone between surface water and groundwater (Ward et al. 1999). Finally, by augmenting the water storage capacity of the river system, floodplains help attenuate peak flows and reduce the risk of extensive flood damage.

Identifying Priority Floodplains

Floodplains are one important component of the active river area framework, an approach to river conservation that accounts for and maps the areas and processes that form, change, and maintain a wide array of habitats and conditions in and along rivers and streams (Smith et al. 2008). The framework is accompanied by a geospatial model of the active river area that was developed for rivers in the northeastern United States by the Conservancy's Eastern Science Office in Boston, MA. The spatial model includes three primary components: floodplains, riverine wetlands, and riparian areas that are likely to contribute woody debris, course particulate organic matter, sediment, and energy to the riverine system. Together, these three components represent the channels and riparian lands necessary to accommodate many of the physical and ecological processes associated with the river system.

We used the active river area model to map floodplains for all rivers in the Delaware River Basin that have drainage areas greater than approximately 40 square miles. In the northeastern United States, two important transitions begin at approximately this size: rivers transition from erosional to transfer and/or depositional zones. Because of these changes to available habitat, fish assemblages also begin to change (Olivero and Anderson 2008). In these zones, lower elevation rivers with gentler slopes begin to widen and meander across a broad valley floor resulting in more extensive floodplains (Schumm 1977).

We also made several enhancements to the active river area model by mapping the extent of various land cover types (e.g., forest, agriculture, and wetlands), protected areas, overlap with FEMA 100-year floodplain, and several other attributes within the active river area "footprint."

Floodplain complexes group floodplain communities occurring under particular environmental conditions, lending insights into ecosystem functionality while also providing a template for floodplain conservation design (Fike 1999). For these disturbance-driven systems, we wanted to base the floodplain assessment on units that are appropriate to the scale of floodplain communities and the dominant processes that form them. Using the mapped patches of natural cover (primarily forest and wetland, with small areas of shrub and grassland) and undeveloped land cover (natural cover plus agriculture), units of analysis were developed that enabled assessment of floodplain composition and condition at multiple scales. These units are referred to as floodplain *cores, corridors, and complexes*. This multi-scale approach allows us to represent a fine level of detail with patches of natural and undeveloped cover, while also being able to combine patches into floodplain complexes of increasing size and extent.

We created the following rules to define and select floodplain cores, corridors, and complexes. Figure 4.1 illustrates floodplain core and corridor patches within a floodplain complex along the mainstem Delaware River. The criteria we applied allowed us to select those areas that have the most potential for floodplain functionality, and therefore, the opportunity for protection and restoration in meaningful places.

1. Cores are defined as contiguous areas of natural cover[1] (predominately forest and wetland cover) greater than 250 acres in the active river area.
2. Corridors embed Cores and are defined as:
   a. Natural and undeveloped cover patches of any size along a stream reach that contains a core patch; and
   b. Natural and undeveloped cover patches greater than 100 acres that are immediately upstream or downstream of a stream reach that contains a core patch.
3. Complexes unite cores and corridors along major rivers and across rivers of different sizes.

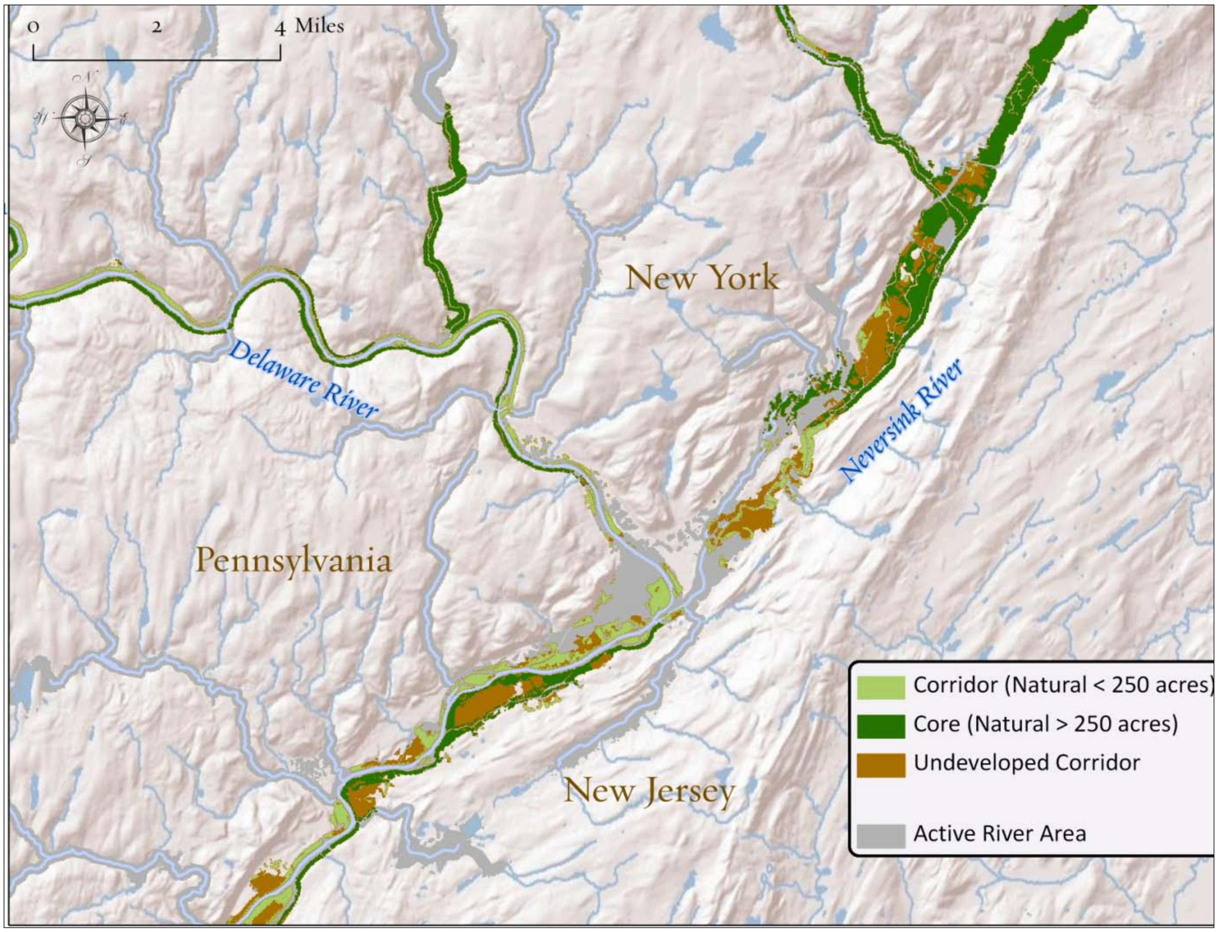


Figure 4.1. Core and corridor patches within the Delaware Water Gap floodplain complex

[1] We defined natural cover using the following classes in the National Land Cover Dataset (2001): Forest (41, 42, and 43); Wetland (90 and 95); Scrub/shrub (52); and Grassland/herbaceous (71). There is very little area that is classified as scrub/shrub or grassland/herbaceous within the active river area of the Delaware. Most of the natural area within the floodplain is either forest or wetland.

By mapping floodplain complexes using the criteria for cores, corridors, and complexes***, we identified sixty-two priority floodplain complexes in the Delaware River Basin: six occur along the mainstem, twelve occur along major tributaries, and forty-four occur along small rivers (Figure 4.2).***

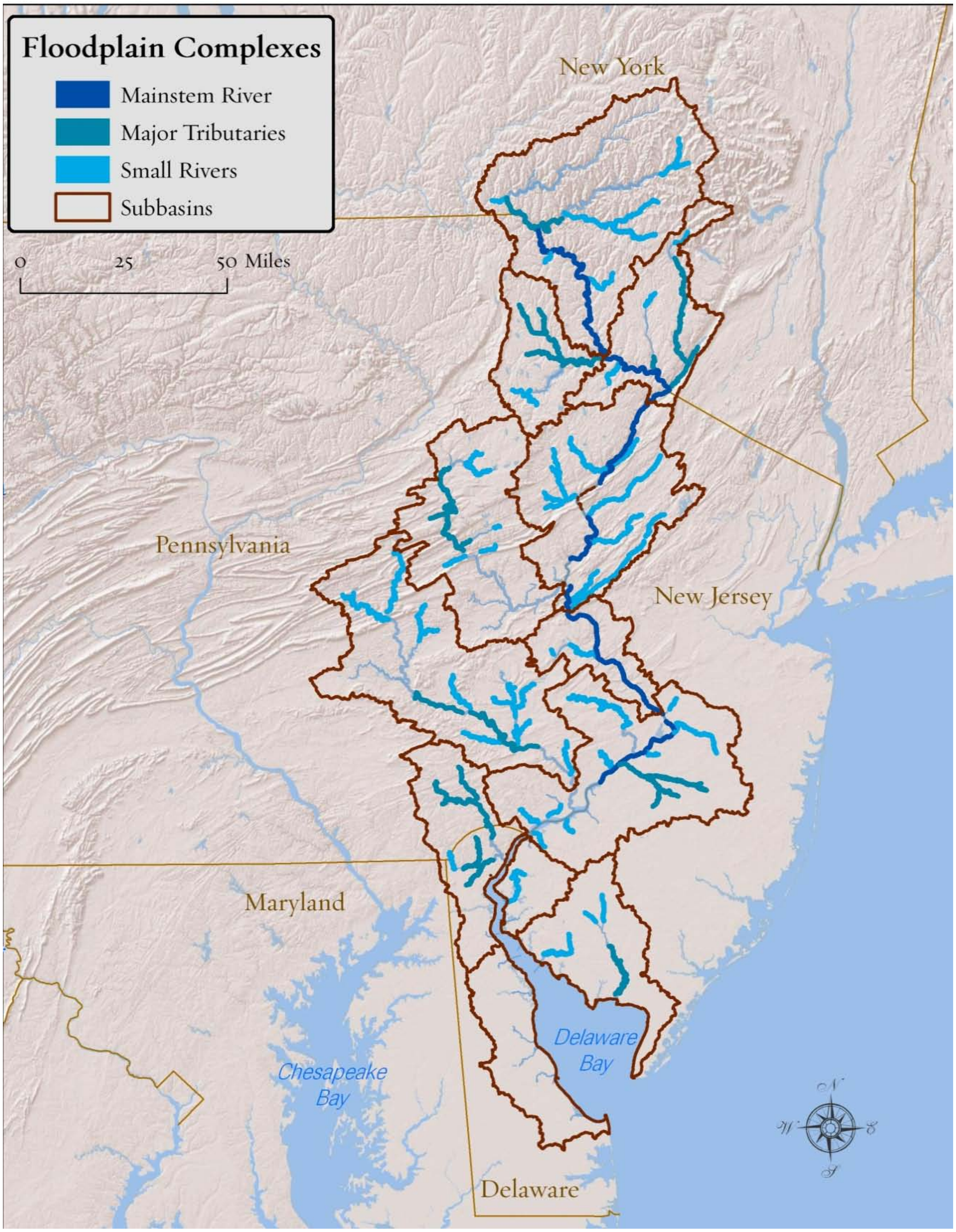


Figure 4.2. Floodplain complexes within the Delaware River Basin

4.1.2 Headwaters

Ecological Importance

Headwaters originate where overland flow and material originating from hillslopes and un-channelized hollows eventually converge to form ephemeral first and second-order stream channels. Headwater systems represent an important transition between physical processes, morphological characteristics, and ecological communities (Gomi et al. 2002; May 2007). Headwaters can constitute as much as 60-90% of the cumulative channel length in mountainous terrains and 70-80% of the total watershed area (Leopold et al. 1964; Schumm and Lichty 1965; Shreve 1969; Sidle et al. 2000; Meyer and Wallace 2001).

A range of processes and attributes sustains the biological diversity of headwaters and downstream systems. Energy sources in headwater systems are primarily coarse and fine particulate organic matter and woody debris that falls into the stream channel from the local catchment. Aquatic insects in headwaters (shredders and detritivores) are adapted to use this energy source efficiently and transfer it up the food chain, supporting the growth and productivity of higher organisms (Bott et al. 1985; Kaplan et al. 2010). Additionally, organic and inorganic materials are periodically exported downstream where they help build food webs and habitats (Vannote et al. 1980; Saunders et al. 2002; Meyer et al. 2007; Wipfli et al. 2007; Smith et al. 2008).

Stream chemistry of headwaters is highly dependent on the region's soil and geology, and flow is highly dependent upon seasonal snowmelt, precipitation, and groundwater contributions. These areas provide variable environments for resident and migrating species. The mixture of groundwater and surface water in headwater springs and wetlands provides spawning areas and refugia during times of temperature- and flow-related extremes, while also shielding species from predators and high flow velocities (Hack and Goodlett 1960; Gomi et al. 2002; Meyer et al. 2007).

Identifying Priority Headwaters

Using results from the Northeast Aquatic Habitat Classification, we defined headwaters as streams with drainage areas less than approximately 40 square miles (Olivero and Anderson 2008). Because headwaters are so abundant and the drainage area associated with headwater streams can comprise such a large proportion of total watershed area, we developed a method to identify areas that are most critical for supporting and maintaining physical and ecological processes associated with headwater systems. This subset of the headwater watershed is referred to as the *headwater stream network*; it is split into two distinct parts: (Figure 4.3):

> **Small headwater catchments** are drained by headwater streams with drainage areas less than approximately 4 square miles. The Northeast Aquatic Habitat Classification System defines streams with drainage areas less than 3.9 square miles as headwaters. This definition captures the majority of first-order streams mapped per the National Hydrology Dataset Plus (Olivero and Anderson 2008). Because maps typically under-represent headwater streams, we represent the smallest headwaters with a catchment rather than a stream line. By including the entire catchment, we capture ephemeral streams and other small headwater streams that may not be

mapped because of inconsistencies in mapping protocols among basins. These small drainages capture the processes and attributes of hillslopes and zero- and first-order basins.

Riparian corridors have drainage areas between approximately 4 and 40 square miles. For streams with drainage areas greater than 3.9 square miles but less than 38.6 square miles, we used the active river area to represent the riparian corridor. In these areas, ephemeral streams eventually transition to perennial first- and second-order streams. Riparian corridors along these streams maintain temperature and sediment regimes, stabilize stream banks, contribute organic and inorganic materials, and regulate nutrient cycling (Peterjohn and Correl 1984; Sweeney et al. 2004; Smith et al. 2008).

Using headwater stream networks has advantages over whole-watershed conservation, which is often extremely difficult and impractical. Headwater stream networks represent discrete areas within watersheds where efforts to reduce impacts of land-based pollution sources and stormwater runoff could have system-wide benefits (Saunders et al. 2002).

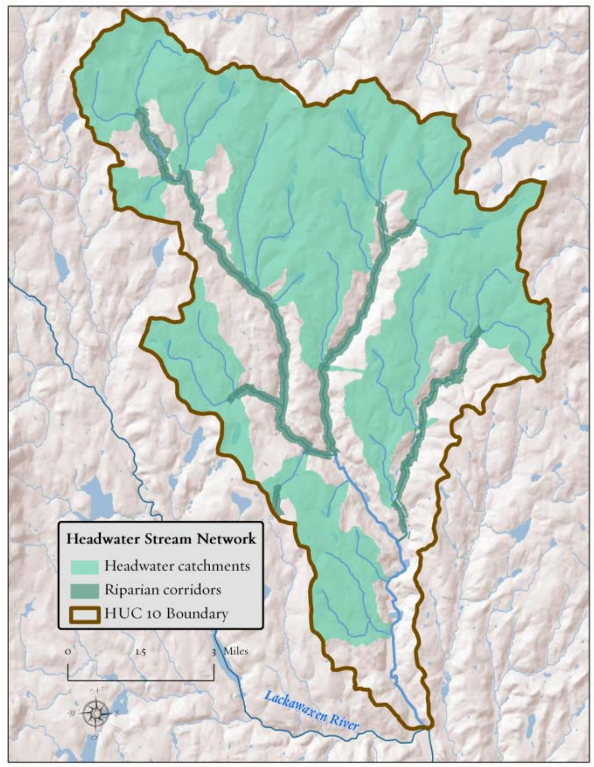


FIGURE 4.3. Headwater stream network for Dyberry Creek, Wayne County, PA. The network consists of small headwater catchments draining headwater streams connected to downstream riparian corridors.

Headwater stream networks can then be organized within watersheds of various scales. Watersheds are useful reporting units, as they define interacting freshwater systems at various scales and constrain the distribution of many freshwater organisms (Sowa et al. 2004; Olivero and Anderson 2008). Many processes critical to populations and communities occur at the small to intermediate watershed scale (Fausch et al. 2002). We assigned each headwater network to the appropriate small and intermediate sized watershed (i.e., HUC 12 and HUC 10) and summarized metrics related to headwater condition at these two scales.

To identify watersheds that include the most physically intact/least altered headwaters within the basin, and to organize headwater stream networks within watersheds, the condition of headwater stream networks at the small and intermediate watershed scale was summarized. We calculated percent of the headwater stream network that is in natural cover and the percent that has low (<3%) impervious surface. Both measures were summarized at the small and intermediate watershed scale, and the least-altered watersheds within each sub-basin were identified. ***We defined these least-altered headwaters as potential priorities for headwater conservation. Figure 4.4 shows the most physically intact headwater stream networks within each sub-basin.***

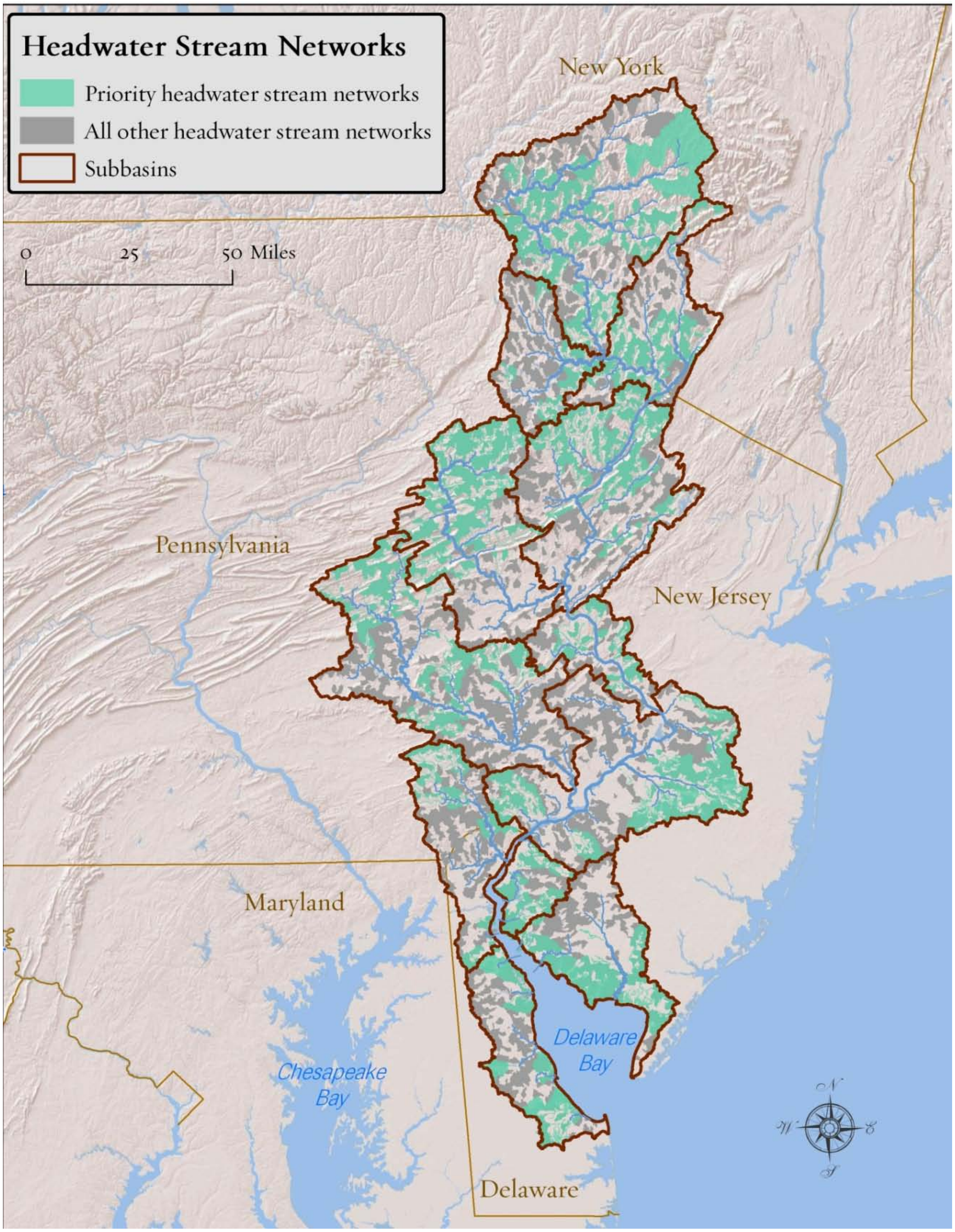


Figure 4.4. Priority headwater stream networks within the Delaware River Basin. These headwater stream networks have the least altered land cover in each major sub-basin.

4.1.3 Non-tidal Headwater and Riverine Wetlands

Ecological Importance

Wetlands – including marshes, 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). The diversity and abundance of wetland vegetation provides food for many species. Wetlands create habitat, (e.g., for breeding) and shelter (e.g., refugia from predators) for species that move between terrestrial and aquatic ecotones as well as for those aquatic species that move upstream into headwater wetlands and laterally into riverine wetlands (NOAA 2001; Dahl 2006).

Wetlands also provide many vital ecosystem functions. Headwater wetlands retain and store precipitation, recharging groundwater resources. They are important sources of water, sediment, and organic and inorganic materials that support downstream aquatic systems. Riverine wetlands provide a local supply of large woody debris and coarse particle organic matter to rivers. Analogous to the kidneys of a freshwater system, headwater and riverine wetlands filter sediment and transform nutrients, thereby improving or maintaining the water quality of small streams and rivers (NOAA 2001; Dahl 2006).

Identifying Priority Headwater and Riverine Wetlands

Within the Delaware River Basin, wetlands were categorized based on tidal influence, salinity, and watershed position (Figure 4.5). This section describes the analysis of non-tidal riverine and headwater wetlands. Analysis of tidal wetlands, including salt marsh and tidally-influenced freshwater wetlands, is described in Section 4.2 – Tidal Marshes.

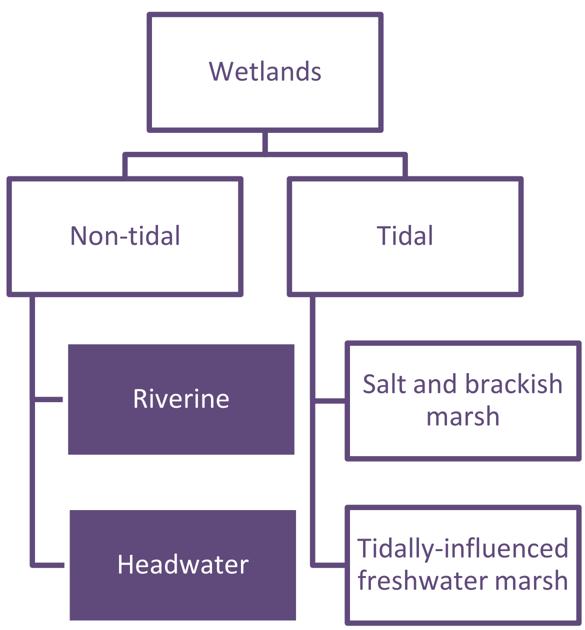


Figure 4.5. Major wetland groups within the Delaware River Basin. Solid boxes indicate the two types of non-tidal wetlands discussed in this section.

We mapped the non-tidal wetlands of the basin and assessed wetland size, abundance, and condition for each sub-basin within the Delaware Basin. Isolating non-tidal wetlands allowed us to highlight 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 non-tidal/freshwater wetlands (Environmental Law Institute 2010).

Wetlands were first defined by selecting the woody and emergent wetland land cover classes from the National Land Cover Dataset (NLCD 2001). Open water features such as ponds, lakes, and reservoirs were not included as wetlands in the analysis. Wetlands were then tagged and divided into tidal and non-tidal wetland classes using the National Vegetation Classification System (NVCS) (Westervelt et al. 2006). This classification includes 35 ecological systems (12 non-tidal) associated with the Upper and Lower Estuary and Bay portion of the basin.

We also separated non-tidal wetlands into headwater and riverine wetlands (Figure 4.6.). Headwater wetlands exist in the small headwater regions of the watershed and along the riparian corridors of small streams. Riverine wetlands exist within the floodplains of rivers with drainage areas greater than approximately 40 square miles.

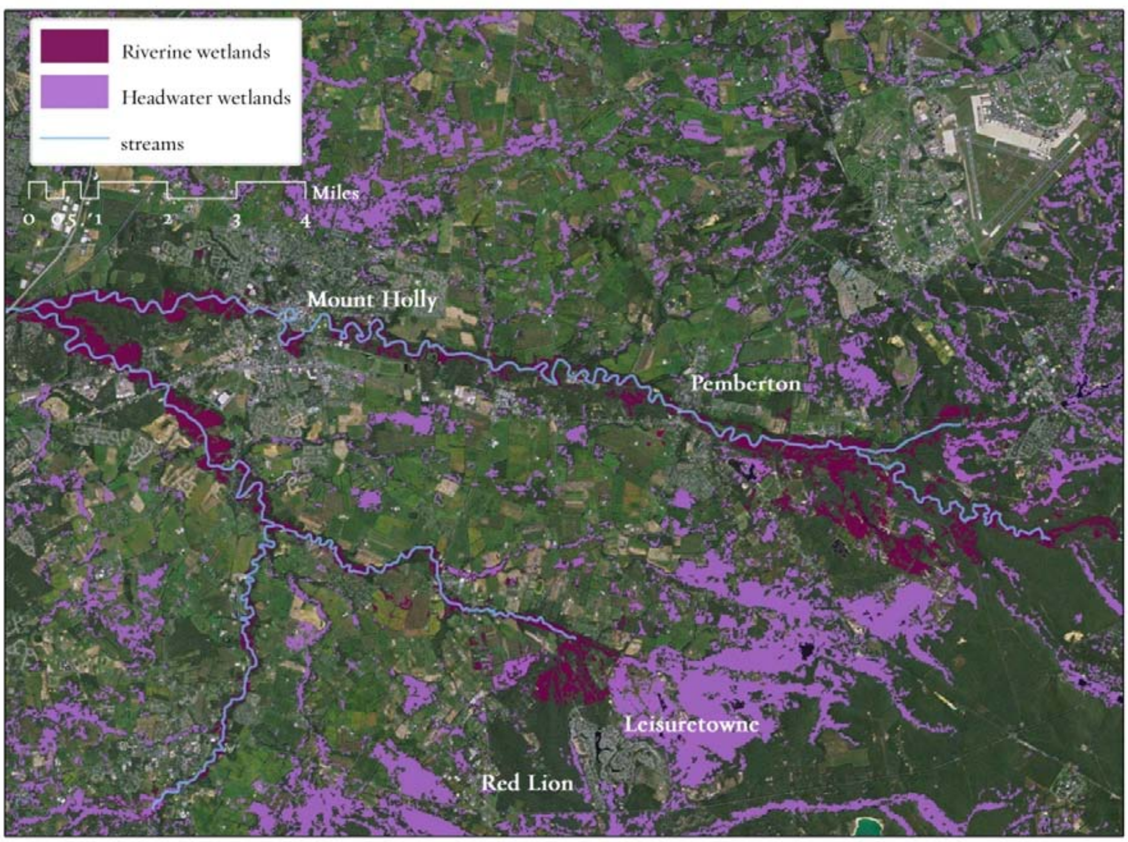


Figure 4.6. Riverine and headwater wetlands within the Rancocas Creek watershed, New Jersey.

Headwater Wetlands: We created a contiguous wetland database that only includes woody and emergent wetlands (based on NLCD 2001) that are also non-tidal (as identified in the NVCS). To do this, we joined wetland pixels that meet these two criteria and that share a side or a corner (i.e., are connected on a side or on the diagonal). The final step in mapping headwater wetlands was to select all contiguous wetlands that were within or overlapped with the headwater stream network "footprint" to include in the headwater wetland analysis.

Contiguous wetlands potentially include multiple wetland types. Since we are primarily interested in wetland function within headwaters, combining adjacent wetland types into contiguous wetlands helps us describe different functional roles that wetlands may play in various portions of the basin because of their size, abundance, and density.

Once contiguous headwater wetlands were mapped, we analyzed wetland size, abundance, and density, characteristics that can guide wetland conservation efforts. For example, the Pennsylvania Comprehensive Wildlife Conservation Strategy (CWCS) emphasizes that conservation of large wetland habitat is especially critical for wildlife conservation (PGC and FBC 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 (or larger). For our analysis, we defined large wetlands as those that are greater than 100 acres.

In addition to wetland size, the relative abundance of individual wetlands (regardless of size) within a watershed is also important. When watersheds contain many wetlands, it becomes increasingly likely that species will be able to move among wetlands to meet their habitat needs. Even small wetlands (less than 12 acres) may serve as important alternate feeding sites and as "stepping stones" during movements between larger wetlands. In addition, in some states' management frameworks, these small wetlands sometimes receive no legal protection (PFBC 2005). To capture these areas, watersheds were identified where the number of wetlands per watershed ranked within the top quartile (the top 25%) of the watersheds within each sub-basin.

Finally, we identified watersheds within the basin where wetland area is concentrated. Dense concentrations of wetland land cover typically represent areas of small and large interconnected wetlands and wetland complexes. To capture these areas, we identified watersheds where the area and percent wetland are high. Specifically, these watersheds ranked within the top quartile for either wetland area or percent wetland.

To summarize, we identified all watersheds that met at least one of the following criteria for wetland size, abundance, or density:

- Contains an individual contiguous headwater wetland larger than 100 acres
- Number of individual contiguous headwater wetlands in the watershed is in the top 25% (by sub-basin)
- Wetland area and percent wetland within the headwater stream network is in the top 25% (by sub-basin)

These watersheds represent potential priority areas for headwater wetland conservation (Figure 4.7). We further analyzed these watersheds using condition metrics described in the next section.

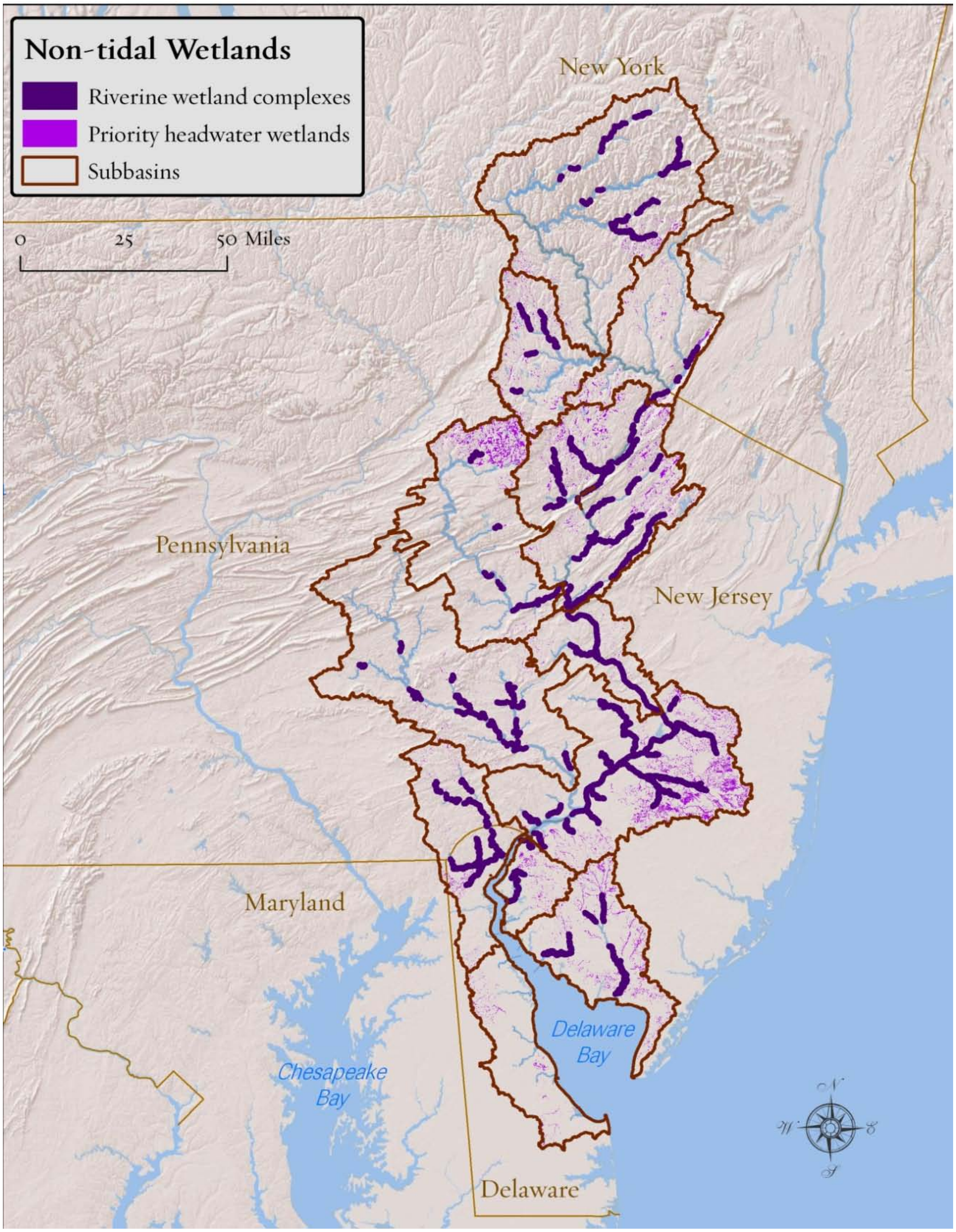


Figure 4.7. Priority non-tidal headwater and riverine wetland complexes.

Riverine Wetlands: For watersheds with drainage areas greater than 38.6 square miles, riverine wetlands were mapped using the NLCD (2001) criteria and the active river area. By overlaying emergent and woody wetlands with the active river area, we mapped contiguous wetland patches within the floodplains and riparian areas of larger rivers.

Once these patches were mapped, riverine wetland complexes were identified using a similar approach to that used for identification of floodplain complexes, except using only wetland land cover (rather than all natural and undeveloped land cover types). We defined wetland cores as wetlands > 10 acres within the active river area. Corridors were developed by adding all wetlands larger than one acre that were along the same stream reach as the wetland core. Finally, we defined riverine wetland complexes as those areas including at least one core wetland and containing at least 50 total acres of wetlands. ***Sixty-four (64) priority riverine wetland complexes were identified using this method (Figure 4.7).*** Many of these riverine wetlands overlap with floodplain complexes identified in the floodplain analysis.

4.1.4 Freshwater Ecosystems Condition Assessment

This section provides an overview of the measures used to evaluate the condition of the three freshwater ecosystems: floodplains, headwaters, and wetlands. The first step in the condition assessment was to describe each system's key ecological attributes (KEAs). KEAs are the aspects of an ecosystem's biology or ecology that, if present, define a healthy system, and if missing or altered, would lead to the outright loss or extreme degradation of that ecosystem over time. Although specific measures vary among ecosystems, the KEAs for all three ecosystems could be grouped into five categories: Aquatic Connectivity, Flow Regime, Landscape Condition, Size, and Resiliency. Following is a brief description of each key attribute; specific measures are highlighted in boldface. Appendix III includes additional information, organized by freshwater ecosystem, including the data sources and thresholds used for each measure.

Aquatic Connectivity

Connected streams are critical for the movement and dispersal of host fish for mussels, for local migratory species, and for diadromous fish species. In-stream barriers can prevent the longitudinal movement of water, sediment, nutrients, organic matter, and aquatic organisms (Ciruna and Braun 2005). Dams can prevent migratory fish from reaching critical habitat.

Using the Barrier Analysis Tool (BAT, Version 1.0, 2010) we identified the extent to which aquatic systems were longitudinally connected upstream through their headwaters and downstream to the mainstem and ultimately to the bay. This tool calculates the available upstream, downstream, or cumulative stream network size that is not blocked by barriers. By adding the length of all tributaries until it reaches either a barrier or a river source, the tool defines the size (length) of each functional or connected network. Figure 4.8 illustrates the connected stream networks of various sizes within the basin.

Using this map, we calculated the *percent of each floodplain complex and headwater stream network that is connected to the bay or within a large functional network* (i.e., greater than 100 stream miles).

In addition, we evaluated the lateral connectivity of floodplains and riverine wetlands by calculating *the area and percent of each complex that is within the 100-year floodplain*. This analysis identifies those floodplains that are still hydrologically connected to the river and further identifies areas of potential flood storage.

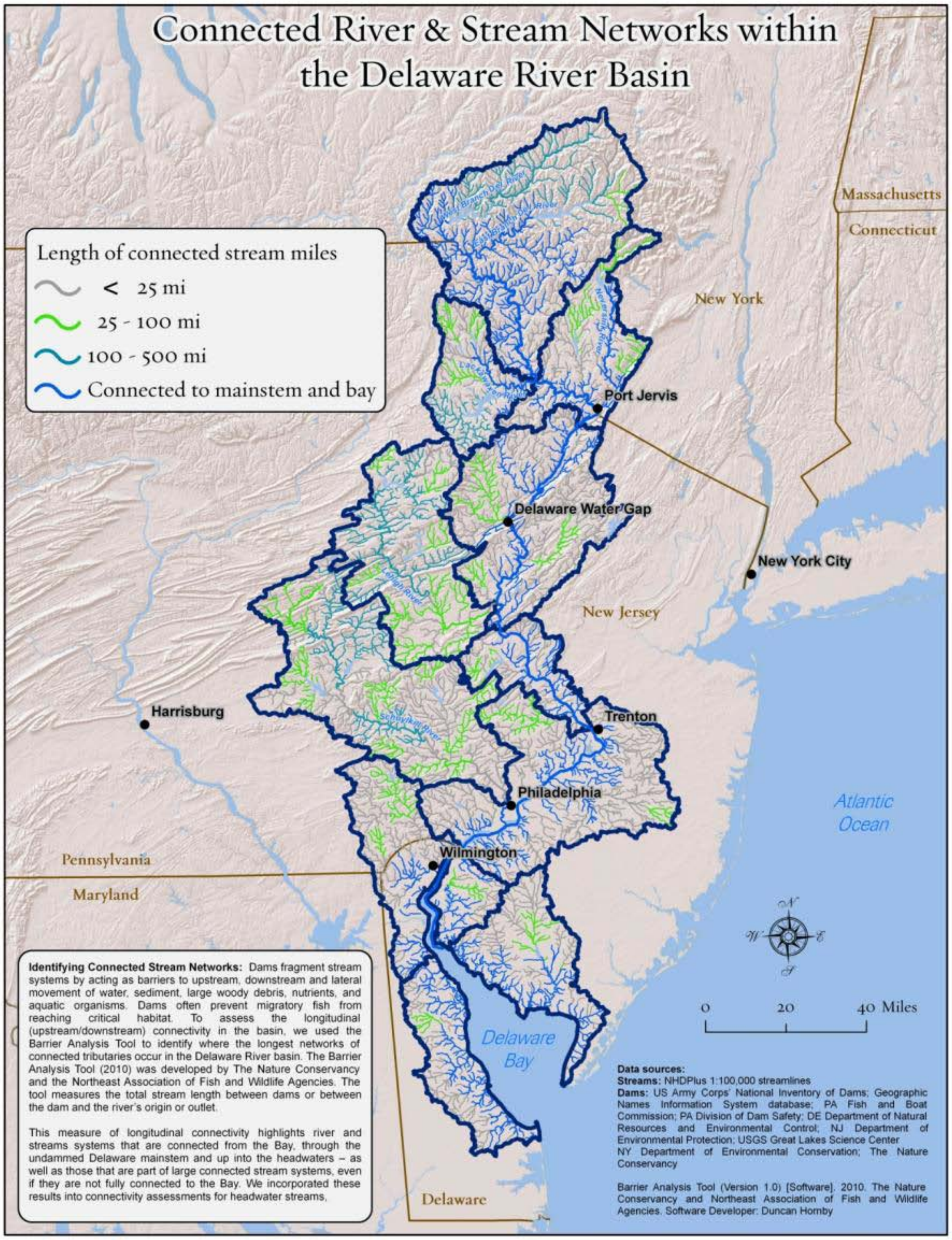


Figure 4.8. Connected River and Stream Networks within the Delaware River Basin.

Flow Regime

Freshwater and riparian ecosystems are highly dynamic, requiring natural variations in water flow to support the processes that sustain their biodiversity over time (Smith et al. 2008). An ecologically functional floodplain requires interaction with a river that retains a flow regime with sufficient variability to encompass the flow levels and events that support important floodplain processes (Opperman et al. 2010). Human-induced alterations to flow magnitude, timing, duration, and rate of change can cause various negative impacts throughout a watershed (Poff et al. 1997). Dams for flood control, hydropower, and water supply not only act as barriers to movement, but they also dampen natural variations in flow.

Several studies have demonstrated increased hydrologic alteration as the dam storage ratio, the ratio of upstream dam storage to streamflow, increases (Zimmerman and Lester 2006; Vogel et al. 2007; Fitzhugh and Vogel 2010). We calculated the dam storage ratio using the sum of upstream reservoir storage as a proportion of mean annual stream flow attributed to each NHDPlus streamline. Cumulative upstream storage values were calculated using the Barrier Analysis Tool (2010). Dam storage ratio was then used as an indicator of the degree of impact dams are having on a given system. We consider reaches with a storage ratio >0.5 (or 50 %) at high risk of hydrologic alteration, consistent with published thresholds (Zimmerman and Lester 2006; Fitzhugh and Vogel 2010). For each floodplain complex and headwater stream network, we calculated the *percent of stream length with a low dam storage ratio*.

This ratio does not incorporate potential hydrologic alterations due to dam operations, which may be as or more important than the volume of water stored. Assessment of hydrologic changes due to dam operations can be carried out when more detailed streamflow and/or operations data are available (e.g., Moberg et al. 2010).

Landscape Condition

The amount and configuration of land cover types within floodplains, headwaters, and watersheds surrounding a freshwater system can strongly influence ecological integrity. Land cover changes affect hydrologic regime, chemical regime, and connectivity between a river and surrounding lands. For example, even low levels of impervious cover (between 1% and 3%) have been shown to have significant impacts on aquatic species (Cuffney et al. 2010; King and Baker 2010). A study of northeastern brook trout populations revealed that in watersheds with less than 82% natural cover, trout populations were likely to be extirpated, whereas in watersheds with greater than 90% natural cover, populations were likely to be intact (Hudy et al. 2005). Natural land cover can help slow down or retain flood waters, sustain natural flow regimes (DVWK 1999a in Sartor 2005), and buffer streams from pollutants and sediments (Fisher and Fischenich 2000).

We used several measures to analyze landscape context for floodplains, headwaters, and wetlands:

- **Area and percent natural cover within floodplain complex**
- **Percent natural cover with headwater stream network and percent of headwater stream network with less than 3% impervious cover**
- **Area and percent natural cover surrounding riverine wetlands**

Size and Abundance

The size of conservation areas needs to be large enough to allow species and ecosystems to recover from natural and anthropogenic disturbances (Groves 2003). This notion of "being large enough" was one of the driving forces behind the development and identification of floodplain complexes, which need to be large enough for species to recover from disturbances such as flooding and ice scour.

Size was also a significant factor in the identification of wetland priorities. Large wetlands are critical for maintaining suitable habitat for priority species in the Pennsylvania Comprehensive Wildlife Conservation Strategy. Conservation of these sites will also support most other priority species in this habitat suite (PGC and PFBC 2005).

In addition to size, density or concentration of contiguous wetlands within the basin's sub-watersheds was also evaluated. Assessing both area and density provides insights into the relative abundance and distribution of wetlands throughout the basin.

We used several measures to analyze the size of riverine and headwater wetlands:

- **Area and percent of wetland within the active river area**
- **Number of contiguous wetlands greater than 25 acres**
- **Presence of at least one wetland greater than 250 acres**

Resilience

Aquatic organisms require refugia to persist during, and recover from, periodic disturbances. As threats to freshwater ecosystems – including climate change and landscape fragmentation – continue to escalate, it becomes even more important to be able to identify and conserve areas that provide potential resilience.

Baseflow is the component of stream flow that can be attributed to groundwater (Wolock 2003). Baseflow helps maintain temperature regimes that support aquatic organisms, enables chemical transfer of nutrients and minerals between surface and groundwater systems, maintains perennial flow in many small headwater stream systems, and augments surface water flows in larger streams (Winter et al. 1998; Fanok 2000; Ciruna and Braun 2005).

Headwaters with high baseflow contributions and low groundwater use may provide refugia to aquatic flora and fauna during times of temperature and flow-related stress. We used groundwater availability data from the United States Geological Survey (Sloto and Buxton 2007) to assess *the volume of groundwater available and the percent of groundwater used* in each headwater network.

We used size (length) of connected functional networks as a measure of aquatic connectivity; this measure may also be used as a potential indicator of aquatic ecosystem resilience, as connected freshwater systems provide places for species to move during times of environmental stress.

Based on the results of this freshwater ecosystem condition assessment, in Section V appropriate conservation strategies are identified for the identified priority conservation areas for headwaters, wetlands and floodplains.

4.2 Tidal Marshes

Tidal marshes can be found in freshwater, brackish, and saltwater environments. The extent and concentration of freshwater tidal marshes, a defining feature of the Delaware Basin, are regionally significant. In the transition zone between non-tidal freshwater systems and brackish or open salt marsh, these marshes (characterized by salinity less than 0.5 ppt) provide an ecotone between the marine and non-tidal environments. Fringing the coast of the bay in a wide swath, salt marsh, with brackish marsh extending up tributaries, forms the bay's dominant coastal habitat type.

4.2.1 Freshwater Tidal Marshes

Ecological Importance

The Delaware Estuary has the most freshwater tidal marsh of any estuary in the U.S. (Kreeger et al. 2010). Forming the interface between the basin's non-tidal freshwater systems and the salty open bay, tidal marshes are highly dynamic systems that connect a range of habitat types and species. Naturally high in diversity (Field and Philipp 2000), freshwater tidal marsh contains both "high" marsh, composed of dominant species like arrow arum (*Peltandra virginica*), spatterdock (*Nuphar luteum*), and pickerelweed (*Pontederia cordata*), and "low" marsh habitat, characterized by species like wild rice (*Zizania aquatica*), cattail (*Typha latifolia*), and common reed (*Phragmites australis*). Freshwater tidal marshes provide important habitat for a range of aquatic and wetland species; in the urban corridor downstream of Trenton, the concentration of this habitat type could be especially significant for species like shortnose sturgeon (Kreeger et al. 2010). Much like salt marshes and other coastal wetlands, freshwater tidal marshes provide an array of benefits for people, as well as wildlife: they maintain water quality by filtering nutrients, sediments, and pollutants (Tiner 1984), they help reduce erosion and buffer storm surges (Stedman and Dahl 2008), and they provide nursery habitat for fish (NOAA 2001).

As important as these freshwater tidal ecosystems are, they have been subjected to a range of negative impacts resulting from human use of the surrounding land. Their position in the estuary exposes them to pollutants, sediments, and nutrients from upstream portions of the watershed (Neubauer et al. 2002). The high concentration of freshwater tidal wetlands in the urban corridor of the Delaware River has been subjected to degradation and destruction via a range of activities and inputs, such as development, highway construction, dredge spoil disposal and landfills, run-off of nutrients and pollutants, chemical and oil spills, and inputs from sewage treatment facilities (Simpson et al. 1983).

Identifying Priority Freshwater Tidal Marshes

Freshwater tidal marshes in the Delaware River Basin currently cover approximately five percent of their historical area (Kreeger et al. 2010). Concentrated along the mainstem Delaware River between Wilmington, DE and Trenton, NJ, the condition of these marshes reflects the effects of negative impacts of intensive land conversion and industrial activities in this urban corridor (e.g., Simpson et al. 1983). Residential and commercial development has left only fragments of freshwater tidal marsh fringing the Delaware and its tributaries in this section of the basin. Discrete but somewhat more intact patches of freshwater tidal marsh occur further upstream in the river systems that drain into the open bay, such as the upper tidal portions of the Maurice River in New Jersey or the St. Jones River in Delaware.

Two different datasets were used to map the extent of freshwater tidal marsh within the Delaware River Basin, as no consistent and comprehensive dataset exists that captures the full extent of these marshes. Primarily relying on the Predicted Ecological Systems data from the Delaware Estuary National Vegetation Classification System dataset (Westervelt et al. 2006), we supplemented these data with significant occurrences mapped by The Nature Conservancy in 2008 along the Maurice River. Because these are riverine marshes, we took an approach somewhat similar to our analysis of floodplain complexes and grouped mapped cells of freshwater tidal marsh into complexes according to clustering patterns along the mainstem or along individual tributaries. Because these wetlands are so highly fragmented due to changes in land use, we did not require that freshwater tidal marsh complexes contain only one contiguous occurrence of tidal marsh cells but instead allowed one complex to contain several discrete patches of nearby freshwater tidal marsh cells. We used a 500-meter buffer, determined by patterns of occurrence clustering, to group patches of marsh into complexes.

Figure 4.9 illustrates patches of freshwater tidal marsh within a complex along the Delaware River and Woodbury Creek.

By mapping tidal marsh complexes in this manner, we identified 54 complexes in the Delaware River Basin that contained at least 10 acres of freshwater tidal marsh within each complex; six complexes contain over 500 acres of area mapped as freshwater tidal marsh. Because this ecosystem type plays such a critical role in the urban corridor of the Delaware River and has been so dramatically reduced in extent over time, ***we considered all freshwater tidal marshes over 10 acres in size to be conservation priorities.***

Figure 4.10 illustrates these priority freshwater tidal marsh complexes across their range in the estuarine portion of the Delaware River Basin.

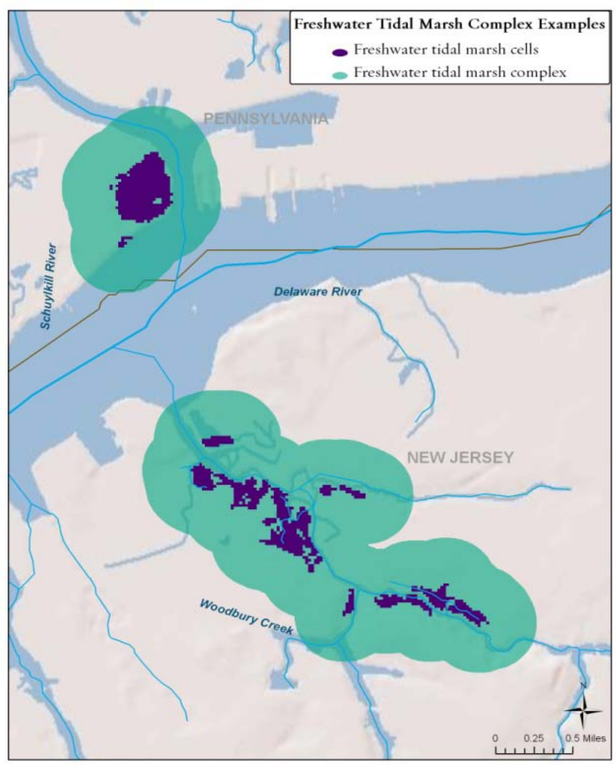


Figure 4.9. Freshwater tidal marsh complex along the Delaware River and Woodbury Creek tributary

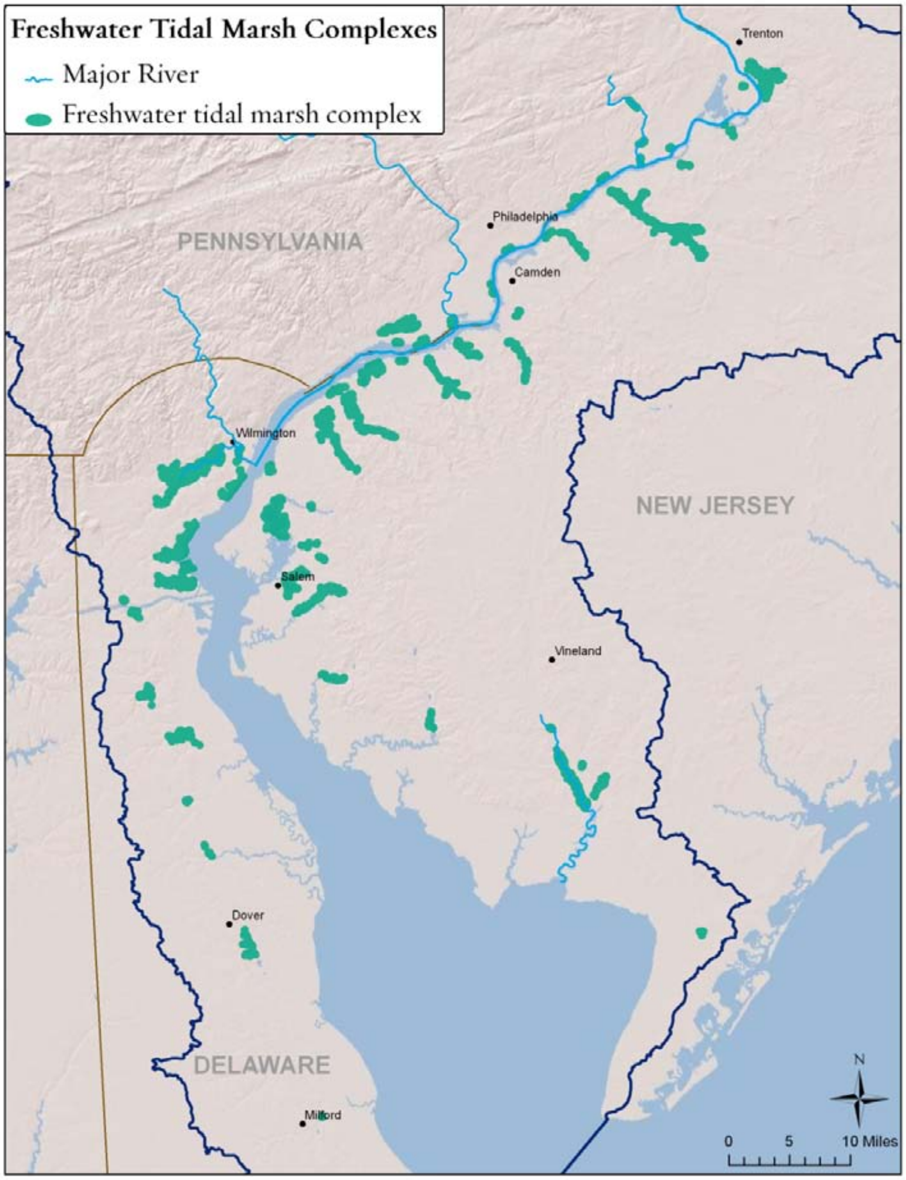


Figure 4.10. Freshwater tidal marsh complexes in the Delaware River Estuary

4.2.2 Freshwater Tidal Marsh Condition Assessment

Although we identified all tidal marsh complexes as priority conservation areas, in order to assign appropriate priority strategies to each complex, we analyzed key ecological attributes of these complexes to determine what types of conservation actions could best help protect or restore these marshes. The three KEAs examined were: (1) sufficient size to allow natural processes to occur and to enable some resilience over time, (2) hydrologic connectivity, and (3) presence of undeveloped surrounding lands indicative of quality of current condition as well as of potential to migrate upstream in response to sea level rise.

Size

The extent of a freshwater tidal marsh can be important for its resilience to disturbance over time (Groves 2003). Larger wetlands may buffer impacts to an entire marsh by slowing or halting some processes that lead to degradation. Large marshes also may be more likely to withstand impacts in a portion of the marsh, as tidal marsh vegetation can repopulate degraded areas nearby. Extant patches of freshwater tidal marsh in the Delaware River Estuary region vary in total acreage, as well as in width and longitudinal extent; development and severe degradation have resulted in significant fragmentation of these marshes.

Assessing the size of each freshwater tidal marsh complex allows identification of the largest areas of this wetland type that remain in the basin, such as those located within the Crosswicks Creek watershed, the Rancocas Creek watersheds, the Darby Creek-Mantua Creek watershed in PA, the Salem River-Delaware River watershed, the Christina River watershed, and the C&D Canal-Red Lion Creek watershed. Measuring marsh size also highlights some of the smaller marshes that are more likely to be vulnerable to a suite of threats; these smaller marshes are concentrated along the mainstem Delaware between Wilmington, DE and Trenton, NJ but also occur further upstream in some of the rivers and creeks in DE and NJ that drain into the Delaware Bay.

Hydrologic Connectivity

Free-flowing streams allow natural fluctuations of freshwater flow into estuaries, resulting in gradients of salinity that support a broad range of vegetation communities, and allowing aquatic organisms to move through both marine and freshwater habitats (Gillanders and Kingsford 2002). Upstream barriers like dams can change processes critical to freshwater tidal marshes, such as downstream transport of both water and sediment (Poff and Hart 2002).

Consequently, we examined two measures related to dams and coastal blockages of stream flow in order to assess their likely impacts on freshwater tidal marshes. The first, distance to the first upstream blockage, revealed which barriers (those immediately upstream) are most likely to be preventing tidal marsh species from moving or migrating upstream, as they would as climate change impacts occur. The second, the amount of water stored by a dam, indicates which barriers would most likely be reducing streamflow and sediment transport downstream (those holding the most water). For this analysis, we used data from US Army Corps' National inventory of Dams, Geographic Names Information System Database, PA Fish and Boat Commission, PA Division of Dam Safety, DE Department of Natural Resources and Environmental Control, and the NJ Department of Environmental Protection. We also mapped culvert and dam data at a fine scale using aerial photos and LiDAR digital elevation models (DEMs) to identify coastal blockages. Systems that likely would benefit the most from projects to restore connectivity include those within the Crosswicks Creek watershed, the Rancocas Creek watersheds, the Darby Creek-Mantua Creek in NJ, the Appoquinimink River-Delaware River watershed, the St. Jones River watershed, and the Dennis Creek-Delaware Bay watershed.

Undeveloped Adjacent Lands

Undeveloped uplands adjacent to and upstream of freshwater tidal marsh are important for both current and future freshwater wetland condition. Altered land cover can negatively affect both the hydrologic and chemical regime of aquatic systems. Even low levels of impervious cover (between 1% and 3%) can significantly affect aquatic species (Cuffney et al. 2010; King and Baker 2010). Additionally, developed lands do not allow room for freshwater marshes to migrate upstream as sea levels rise and/or salinity levels increase. Allowing space for marsh migration is a key strategy for sea level rise adaptation (CCSP 2009).

We assessed two closely-related measures pertaining to undeveloped adjacent lands. First, we determined the percent cover of natural land within the 500-meter buffer surrounding the extent of the freshwater tidal marsh within each complex to illustrate the range in likely current land use impacts. We also evaluated the acreage of undeveloped lands both adjacent to the freshwater tidal marsh extent and within the active river area, whose lateral extent out from a river channel is limited by slope and elevation. This second measure gives an indication of the amount of room to move a marsh might have as conditions (salinity and/or water levels) at the current extent of freshwater tidal wetlands become unsuitable. Freshwater tidal complexes currently surrounded by a high percentage of natural cover include those in the Raccoon Creek-Delaware River watershed, the Lower Maurice River watershed, and the Dennis Creek-Delaware Bay watershed. Similarly, those with the largest amounts of adjacent undeveloped lands were found in the Raccoon Creek-Delaware River watershed, the Appoquinimink River-Delaware River watershed, the Salem River-Delaware River watershed, the Lower Maurice River watershed, and the Dennis Creek-Delaware Bay watershed.

Based on the results of this freshwater tidal marsh condition assessment, in Section V appropriate conservation strategies are identified for the priority freshwater tidal marsh complexes.

4.2.3 Brackish and Salt Marshes

Ecological Importance

The Delaware Bay is fringed by a contiguous band of brackish/saltwater tidal marshes from the mouth of Delaware Bay upstream to the Delaware Memorial Bridge. Beyond the tidal marsh fringe, tidal wetlands are predominately tributary-associated freshwater tidal wetlands that occur in discrete patches. Salinities in polyhaline salt marshes near the mouth of the Delaware Bay range from 18 to 30 parts per thousand (ppt) and are dominated by two grass species, smooth cordgrass (*Spartina alterniflora*) and salt-meadow cordgrass (*Spartina patens*). Brackish (oligohaline and mesohaline) marshes, with higher vascular plant diversity than salt marshes, occur upstream of the bay mouth in salinity ranges from 0.5 to 18 ppt (Odum 1988). These habitats provide a critical buffer between the tidal ocean and bay aquatic environments and the upland habitats of the Delaware Estuary.

Tidal marshes are widely recognized for their ecological importance, as well as their importance to human populations. Tidal marshes filter contaminants and nutrients, improve water quality, sequester carbon, and protect coastal communities from flooding (Kreeger et al. 2010). A wide range of terrestrial and aquatic species, including birds and commercial and recreational fish and crustacean species, use tidal marsh habitats for nursery grounds and other functions during their life cycles (Boesch and Turner 1984; Nixon 1980).

Identifying Priority Brackish and Salt Marsh

There are more than 145,000 acres of salt and brackish marshes in the Delaware Estuary (Kreeger et al. 2010) (Figure 4.11). Our analysis included all of these marshes along with the associated coastal watersheds that drain into them. We used the National Wetland Inventory (NWI) dataset to capture the extent of tidal marshes fringing the Delaware Bay and the lower estuary. We then identified and mapped all watersheds that drain into the tidal marsh. Due to the importance of tidal marshes in the Delaware Estuary, and the fact that they function as one, unfragmented whole system, ***all fringing tidal brackish and salt marshes are identified as priority conservation areas.***

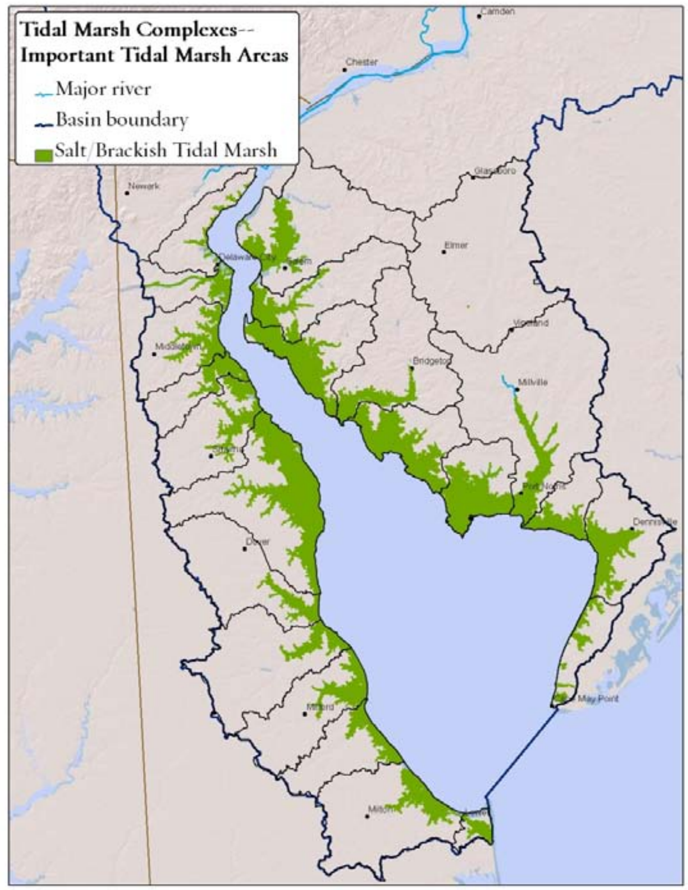


Figure 4.11. Delaware Bay salt marsh complex

4.2.4 Brackish and Salt Marsh Condition Assessment

The current condition of tidal marshes in the Delaware Estuary has been affected by a series of anthropogenic and system-wide threats. Tidal marshes have been altered since colonial settlement along the Delaware Bay by farming practices, mosquito control, and other human uses (Sutton et al. 1996). Although many of these activities have ended, their legacy continues to affect tidal marshes today.

The foremost present-day threat is sea level rise (CCSP2009). In their report *Climate Change and the Delaware Estuary*, The Partnership for the Delaware Estuary identifies sea level rise as the greatest threat to tidal wetlands in the Delaware Estuary. As sea levels rise, tidal marshes are rapidly eroding at the seaward edge and vulnerable low-elevation marshes are being lost as they are transformed into open water (Kreeger et al. 2010). The manipulations of human use and the threat of sea level rise combine to increase the vulnerability of Delaware Estuary tidal marshes. Action is needed to restore degraded marshes, protect natural areas that are in good condition, and allow for the upland movement of marshes as sea level rises.

This analysis focused on four key ecological attributes of tidal marsh condition: hydrologic regime, connectivity, native species composition, and watershed integrity. Data were gathered and analyzed for a series of indicators of current condition for each KEA in order to assess the current condition of the contiguous band of brackish and salt marshes along the Delaware Bay. Through personal outreach and stakeholder input at partner workshops, we determined that the measures should be used in two different ways: (1) to quantitatively describe the current condition of the tidal marshes, and (2) to identify priority conservation strategies within each watershed across the analysis extent.

To further refine our analysis we used selected measures to provide further information that can be applied in each watershed in the analysis (Figure 4.12). This information will allow users to better understand the surrounding landscape condition of tidal marshes and compare key attributes across watersheds. Some of the measures also point to broad conservation strategies that could be applied to entire watersheds, as discussed in Section V. By setting thresholds for measures that link to strategies and identifying opportunities we determined the priority conservation strategies for each watershed in the analysis extent. More detail about these measures and thresholds, as well as summary maps for each measure and data sources, can be found in Appendix IV.

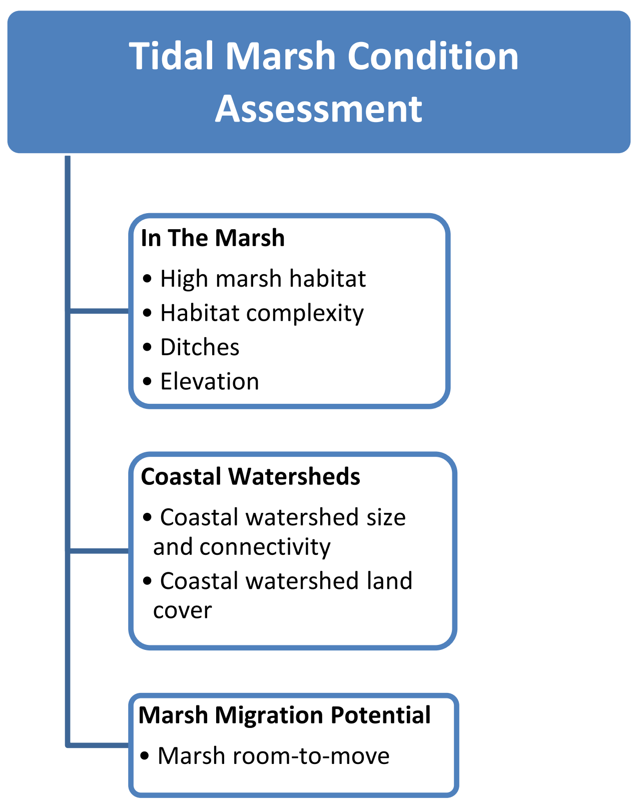


Figure 4.12. Brackish and salt marsh measures used for condition assessment

High salt marsh habitat

High salt marsh is a primary breeding habitat for several species of conservation concern (e.g., salt marsh sparrow and black rail (Donnelly and Bertness 2001), and is more vulnerable to sea level rise than other salt marsh types (Donnelly and Bertness 2001). In the salt and brackish marshes of the estuary, high salt marsh habitat is dominated by salt-meadow cordgrass (*Spartina patens*) and saltgrass (*Distichlis spicata*).

To create a map of high marsh habitat, Delaware Natural Heritage Program habitat mapping data were utilized for Delaware. In New Jersey, there is no high-resolution map of high salt marsh. To automate high marsh mapping, Feature Analyst software (version 5.0, Overwatch Geospatial 2010) was used in conjunction with 2006 National Agriculture Imagery Program. In this true-color growing season imagery, high marsh is easily distinguished from surrounding *Spartina alterniflora* and *Phragmites australis*-dominated marsh. Feature Analyst software created high marsh maps, which were supplemented with ground-truthing where vegetation composition was not clear from aerial photos.

High marsh habitat dominated by *Spartina patens* and *Distichlis spicata* is unevenly distributed in the bay's salt marshes. Salinity limits the distribution of this habitat in the upper bay. In Delaware, there are approximately 5,000 acres of high marsh habitat, with the majority (68%) in the Leipsic River unit. New Jersey's salt marshes contain approximately half the acreage of Delaware's (2,450 acres), with the majority of this habitat in the Stow Creek unit of the state (73%).

Marsh ditching

There is a long history of marsh alteration for mosquito control in the Delaware Bay region, and few areas are untouched by these practices. Ditching marshes alters natural marsh hydrology, reduces the availability of certain habitats (e.g., ponds), and fragments interior marshes (Lathrop et al. 2000).

We used Natural Hydrologic Dataset high resolution flowlines tagged as ditches and hand digitized additional areas using aerial photos to supplement this dataset. We calculated the relative density of ditches across the marsh area by rasterizing these line data (30m resolution) and calculating the Fragstats Edge Density metric in a 1000 m circular moving window.

Our evaluation of the distribution of mosquito ditches in the region's marshes reveals that the intensity of ditching varies around the bay. In Delaware, there are approximately 300 miles of ditches throughout the marshes, including high concentrations of ditches in the Broadkill, Mispillion, Murderkill, and Leipsic River watershed units. In New Jersey there are approximately 260 miles of ditches, with the highest concentration in the Dennis Creek, Lower Maurice, and Stow Creek watershed units.

Habitat Complexity

Areas of higher native habitat diversity can support higher levels of biological diversity (McKinney et al. 2009; Tews et al. 2004) and the presence of the full suite of salt marsh habitats in an area can in some cases indicate a lack of past disturbance.

We created a habitat mosaic (30 m resolution raster layer) representing low marsh, high marsh, *Phragmites*, large creeks, small creeks, and ponds for the marshes of the study area. To create this mosaic we used NHD High Resolution data for waterbody data to identify large creeks and salt marsh ponds and flowlines to identify smaller creeks, high marsh habitat maps described above, Phragmites maps from Delaware Natural Heritage and Rutgers CRSSA 1995 Landcover classification, and marsh area boundaries based on NWI-classified estuarine and marine wetlands.

Habitat diversity was then calculated in a 1000 m circular moving window across this mosaic using Fragstats software. For this diversity metric we excluded *Phragmites*, so that areas with only *Phragmites* would receive the lowest habitat diversity score.

The composition of salt marshes shows considerable variation along the bay. Marshes in the upper reaches of the bay show the least complexity, largely the result of the dominance of *Phragmites australis* in the more brackish marshes. The distribution of salt marsh ponds and pannes around the bay has been reduced by mosquito control activities that have modified these features to promote tidal flow. The distribution of high marsh may be influenced by past farming and diking practices. The areas with the greatest habitat complexity in the bay are the Leipsic River unit on the Delaware side and the Dennis Creek unit on the New Jersey side of the bay. These areas contain the full complement of low marsh, high marsh, pools and panes, and large and small tidal creeks.

Marsh elevation

Past land use practices have altered salt marshes through compaction, biomass removal, and decreased accretion rates (Weishar et al. 2005). These alterations can result in marsh areas with unnaturally low elevations that are vulnerable to future sea level rise. To analyze marsh elevation across Delaware Bay salt and brackish marshes, we used LiDAR-derived DEMs.

LiDAR has important limitations in marsh habitats that prevent detailed analyses of marsh elevation. Nonetheless, this tool can be useful for identifying areas of particularly low elevation that are vulnerable to sea level rise. We mapped LiDAR data in the marsh area and classified it by standard deviations around the mean. The data were then smoothed using the Focal Statistics function in ArcMap to calculate a mean across an eight-cell moving window. Areas that were one standard deviation below the mean marsh elevation were identified as low-elevation marsh.

Low-elevation areas appear in discrete patches throughout the bay's marshes. These are either (1) areas within the marsh that were formerly vegetated and are now primarily sparsely vegetated, open, tidally-flooded areas, or (2) active diked salt hay farms with surface elevations that are below the surrounding marsh elevation. Many of the formerly vegetated areas appear to have been in salt hay production in the past, based on an examination of historical aerial photos. These open areas are found from near the upland edge of the marsh adjacent to coastal communities outward to the fringe of tidal marsh at the edge of the bay. In Delaware these low elevation areas occur in the St. Jones, Murderkill, Mispillion and Broadkill River units. In New Jersey every unit has at least one discrete low elevation area, with the greatest concentration in the Dennis Creek and Lower Maurice River units. The processes that created these low-elevation conditions are not well understood, but under any scenario, these areas will be the first to succumb to the effects of sea level rise.

Shoreline development

Shoreline development interferes with the natural response of shorelines to changing conditions such as rising sea levels and storms (Fitzgerald et al. 2008) and reduces habitat availability for species dependent upon Delaware Bay beaches.

Rutgers CRSSA shoreline data were used to map developed shorelines of the bay. We supplemented these data by hand-digitizing shoreline development in the upper reaches of the bay which were not mapped by Rutgers. Any beaches with houses along the shore or shoreline hardening features such as rip-rap, roads, and jetties were considered to be developed. We also considered dykes that run parallel to beaches to be a form of development because they prevent inland beach transgression. We summarized these data by HUC10 watershed units and calculated percent shoreline development for each unit.

The majority of the bay's shoreline remains undeveloped, with roughly 65% of the shoreline in a natural state. In Delaware the developed portion is concentrated in the Broadkill, Mispillion, St. Jones, and Smyrna River units. In New Jersey, development is concentrated in the Dennis Creek, Lower Maurice, and Stow Creek units.

Undeveloped adjacent uplands

Undeveloped uplands adjacent to salt marsh allow for the inevitable process of coastal transgression, where beaches and marshes move inland as local sea level rises. Allowing space for marsh migration is a key strategy for sea level rise adaptation (CCSP 2009).

To identify areas where marsh migration would not be interrupted by human development, we evaluated connectivity between terrestrial and wetland habitats. First, an upland buffer of irregular width adjacent to coastal wetlands was delineated. The buffer extended from the upland/wetland interface to an elevation of six meters. Within this buffer we assessed connectivity between the upland/marsh edge and the far-upland side of the buffer area. Features that interrupted connectivity were development, roads, and dams. We considered traversable areas to be those with natural or agricultural land cover, stream corridors, bridges, and culverts. Beyond interruptions from development, roads, and dams, we also incorporated slope data from LiDAR DEMs to account for the increased resistance to marsh migration of steeper-sloped areas. We simplified the resulting raster into discrete polygons that represented corridors between the wetland and upland side of the buffer.

In New Jersey, the areas are dominated by forested cover in the Dennis Creek, Lower Maurice, while farmland is adjacent to the marsh in the Cohansey unit. The Stow Creek unit has significant opportunities, where both forested and agricultural lands sit adjacent to salt marshes. In Delaware, the majority of undeveloped adjacent uplands are farms, distributed along the bay shore in the Mispillion, Murderkill, Leipsic, and Smyrna River units. Forested adjacent uplands exist in the Mispillion and Broadkill units as well.

Natural land cover in the watershed

Non-point source run-off from agricultural and developed landscapes can be a significant stressor on estuarine habitats (Rodriguez et al. 2006; Basnyat et al. 1999). Nutrient runoff in particular can cause eutrophication of the estuary and shifts in food webs (Valiela and Bowen 2002). We linked results from the NLCD 2001 NHDPlus Catchment Allocation and Upstream Accumulation Attributes tool to NHDPlus catchments in our analysis area, yielding an accumulated upstream percent natural land cover for each catchment in our analysis area.

Land cover is predominately agriculture in the coastal drainages of Delaware, while in New Jersey several areas are dominated by natural land cover. These units include Dennis Creek, Upper and Lower Maurice River, and a large part of the Stow Creek unit. The Cohansey unit and the upper part of the Stow Creek unit are dominated by agricultural land cover.

Natural land cover in the watershed was used as an indicator of current landscape condition of the tidal marshes' surrounding lands. We applied this measure by quantifying acreage of natural lands and agricultural lands within each priority watershed unit.

Coastal watershed connectivity

Estuaries are, by definition, a product of the interaction between freshwater and marine ecosystems. Free-flowing river systems are essential for this interaction because they allow freshwater to flow into estuaries, provide marine organisms access to freshwater habitats, and create gradients of salinity that result in a broad range of vegetation communities (Gillanders and Kingsford 2002). Aquatic connectivity is important for a variety of ecological functions and serves as a key driver of biodiversity patterns in estuaries. Connected streams have a greater diversity of vegetation along a salinity gradient and allow populations of anadromous fish to access upstream spawning areas.

To examine coastal watershed connectivity, we used dam data from US Army Corps' National inventory of Dams, Geographic Names Information System Database, PA Fish and Boat Commission, PA Division of Dam Safety, DE Department of Natural Resources and Environmental Control, and NJ Department of Environmental Protection. We also mapped bridge, culvert, and dam data at a fine scale using aerial photos and LiDAR DEMs.

We used two parameters to assess freshwater connectivity in tidal marshes:

1) The length of the freshwater network connected to the bay. Using TNC's Barrier Assessment Tool (2010), we identified the length between the Delaware Bay and the first upstream barrier for each stream network.
2) The percent of the watershed connected to the bay. We divided the length of the freshwater network connected to the bay by the TOTAL number of miles of all streams and tributaries in each network.

Results indicate that there are numerous small, free flowing streams that are connected to the bay from headwaters to the salt marsh. The best examples of these occur in the Dennis Creek and Maurice River units in New Jersey and the Leipsic River in Delaware. The longest reaches of connected streams occur in the larger rivers such as the Maurice and Cohansey in New Jersey and the Murderkill in Delaware.

Overall ecological integrity of salt marshes

Since all brackish and salt water tidal marshes were identified as priority areas, and due to the difference in function of freshwater and tidal marsh ecosystems, we were able to assess their overall condition. All measures of ecological condition were combined to arrive at an overall index of ecological integrity for the salt marshes of the basin. We weighted the measures to correspond with the weight of scientific evidence for the role that measure plays in the integrity of these coastal ecosystems.

We summed our array of ecological integrity measure using GIS, weighted by ranked importance (Table 4.1) to yield an overall measure of ecological integrity for salt marshes. In an effort to validate this result, we used a dataset from an on-the-ground assessment (Kreeger 2009) of salt marsh ecological integrity from three watersheds in Delaware. We examined the correlation between the integrity value of on-the-ground samples and the corresponding 30x30m raster cell resulting from our analysis. Based on 109 survey points in the St. Jones, Murderkill, and Broadkill watersheds we found a significant correlation between our GIS-based index of tidal marsh integrity and the field-based assessment of integrity (Spearman's rank correlation, $\rho = 0.32$, $p < 0.0005$).

Several patterns emerge from our composite of ecological integrity measures for salt marshes. In Delaware, the Leipsic unit ranks highest for overall ecological integrity (Figure 4.13). In New Jersey, the Dennis Creek unit has the highest ecological integrity. Delaware marshes generally have higher ecological integrity scores than those of New Jersey, primarily because of the greater abundance of high marsh and lower prevalence of significantly degraded marsh areas. Many of New Jersey's coastal watersheds are dominated by natural land cover.

Metric	high importance	med importance	low importance
High salt marsh	●		
Habitat complexity			●
Marsh elevation	●		
Marsh ditching		●	
Shoreline development	●		
Undeveloped adjacent uplands	●		
Natural land cover in watershed		●	
Freshwater connectivity	●		

Table 4.1. Weighting scheme for tidal marsh ecological integrity measures

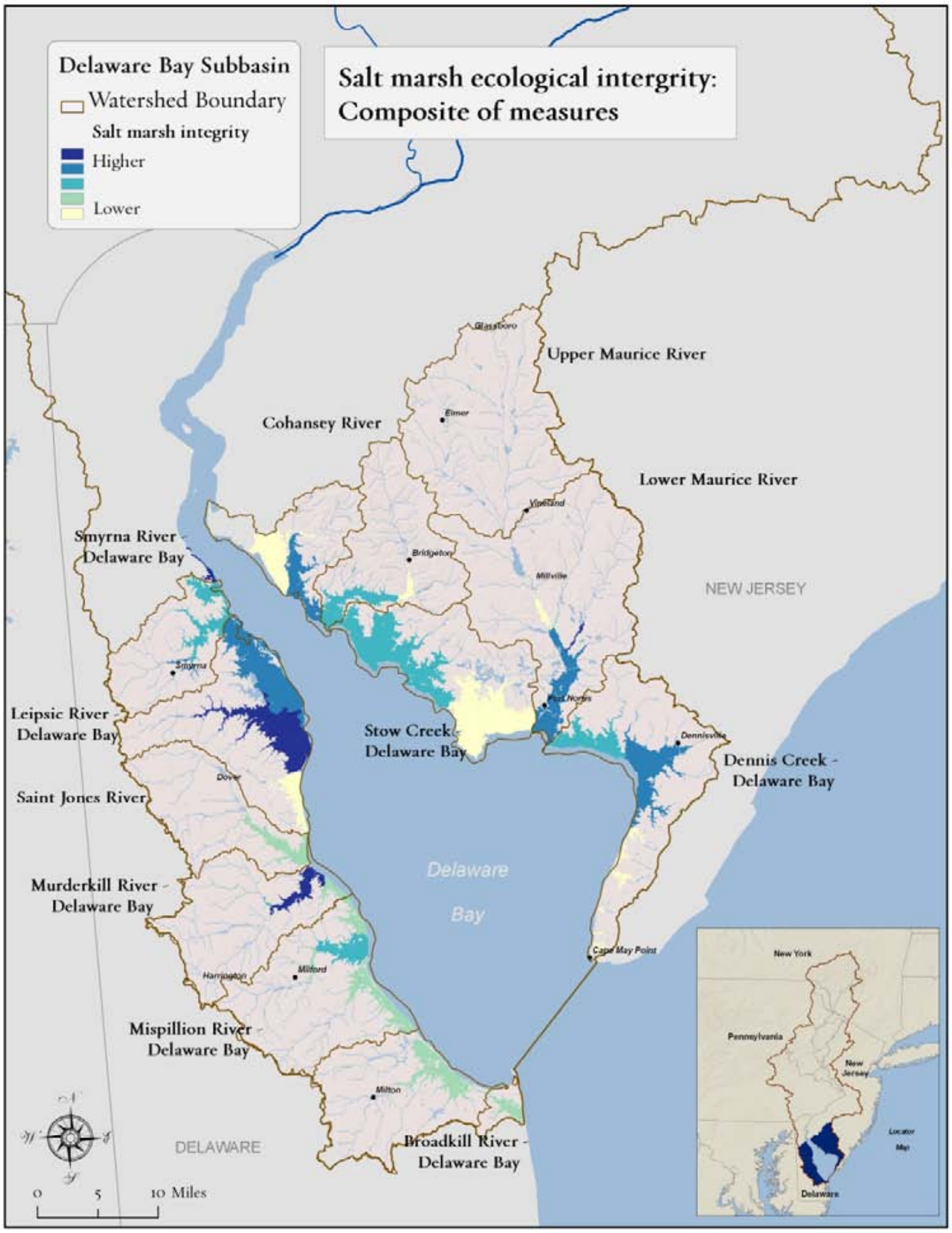


Figure 4.13. The ecological condition of Delaware Bay salt marshes, based on a composite of the measures of ecological condition. Results are summarized by HUC-12 sub-watersheds.

Based on the results of this tidal marsh ecosystem condition assessment, in Section V appropriate conservation strategies are identified for the identified priority conservation areas for brackish and salt water tidal marshes.

4.3 Marine Bivalve Habitat

Although there are at least a dozen marine bivalve species in the Delaware Estuary, we focused on the two species that are considered most ecologically or commercially significant: eastern oysters and ribbed mussels. Both species are important for the creation of habitat (e.g., oyster reefs) and the protection of other ecosystem targets (e.g., ribbed mussels in tidal marshes). For more information on the status, trends and current ecological and economic importance of marine bivalve shellfish in the Delaware Estuary see Kreeger and Kraeuter (2010) and Kreeger at al (2011a).

4.3.1 Oysters and Reef Habitat

Although all bivalve species habitats provide a range of benefits to people and the ecosystem, some species are valued more for their economic and socio-historical importance whereas others are valued for their ecological benefits. For example, Eastern oysters (*Crassostrea virginica*) are the kingpin of the commercial shellfishery in the Delaware Estuary. Oysters are also valued as a culturally and historically iconic species that resonates with the public. They benefit water quality, provide fish habitat, and can help buffer coastal flooding, as well as support recreational and commercial fishing.

Eastern oysters create and live on reefs or scattered clumps of just a handful of individuals in the Delaware Estuary, with some beds in the tributaries. Oyster reefs increase habitat complexity, diversity, and abundance of other organisms, as well as provide ecosystem services such as water quality enhancement (Coen and Grizzle, 2007) and buffering of coastal flooding.

Based on stock assessments for Delaware Bay oyster fisheries in both New Jersey and Delaware, along with local knowledge about populations in tributaries and production on leased grounds, we estimate that there are about 4 billion adult oysters alive in the system today; approximately half live in tributaries and marshes and the other half on the main beds in the bay. Despite these numbers, TNC's report "Shellfish Reefs at Risk" stated that the overall condition of the oyster stock in Delaware Bay is poor, having suffered 90-99% losses compared to historic populations (Beck et al. 2009), primarily attributable to oyster diseases. However, due to enhancement of populations by planting juvenile oysters from other systems in Delaware Bay to increase production for the oyster industry oyster stocks have been generally stable since the 1990s (the "post-Dermo era").

It is difficult to reconstruct historic oyster stock size, since Delaware Bay oysters were actively manipulated and managed before the recorded history of the area. Native Americans were said to have travelled great distances to harvest oysters (Weslager 1944; Weslager 1972; Ford 1997), and the first known oyster map of the bay dates back to Swedish colonies in 1655. By 1719, overharvesting led New Jersey to enact laws restricting harvest (Ford 1997). To keep up with demand and supplement natural recruitment, oyster seed was imported to the bay by the millions of bushels per year, reaching its peak in the period between 1880 and 1950 (Ford 1997). In its heyday, the oyster fishery in the Delaware Bay supported more millionaires per square mile in Port Norris NJ than anywhere else in the United States (Ford 1997). It is important to recognize that these oyster boom times were subsidized in large part by the importation of oyster seed from outside the bay, and augmented by manipulation tactics such as transplanting seed and adults within the bay to increase productivity and boost harvests. Shell planting to boost oyster populations began in the 1950s, a practice that continues today. Most recently the Oyster Restoration Task Force has worked to raise funds and awareness for shell planting starting in 2005.

In the late 1950s, the first wave of oyster disease (MSX, *Haplosporidium nelson*) hit Delaware Bay (Ford 1997). Importation of oyster seed was stopped out of fear that this practice brought in the disease. The areas hardest hit by disease were on the leased grounds in the open bay (Figure 4.14). Because up-bay seed beds were not hit as hard by disease, they became the main source of oyster seed and harvest when imports were stopped. The seed beds had never been able to support the seed demand of the lease beds during the boom times, and the situation became more strained as a result of the disease pressure on the lease beds (Ford 1997).

Today, oysters in the NJ portion of Delaware Bay are managed under an Area Management Plan. The plan is managed by the New Jersey Department of Environmental Protection through the Bureau of Shellfisheries, the Haskin Shellfish Research Laboratory (Rutgers University) and the Delaware Bay section of the Shellfish Council. These three entities work through the efforts of the Delaware Bay Section of the New Jersey Shell Fisheries Council, Stock Assessment Review Committee, Oyster Industry Science Committee, and the oystermen.

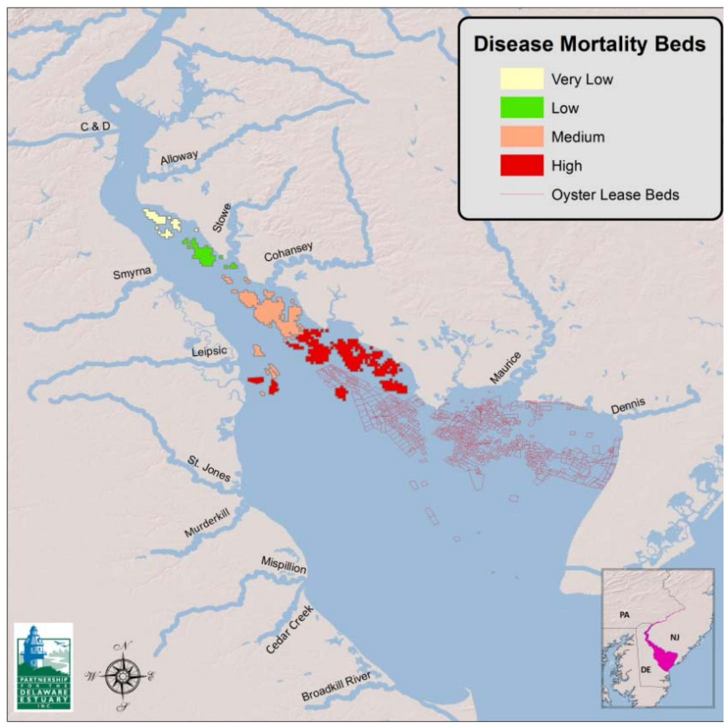


Figure 4.14. Oyster disease mortality zones in the Delaware Bay

Together, these groups are responsible for making annual decisions regarding planting, transplanting, monitoring disease and condition, setting harvest quotas, and self-regulating enforcement (Powell et al. 2011). On the Delaware side, the Delaware Department of Natural Resources and Environmental Control is the primary coordinating entity. The Oyster Restoration Task Force works with all these groups to help raise support, partly from voluntary industry contributions to a cultch fund, for shell planting projects.

4.3.2 Ribbed Mussel and Marsh Habitat

Ribbed mussels (*Geukensia demissa)* are an intertidal species that are found primarily in association with tidal salt marsh plants. Ribbed mussels thrive in salinity ranges of 12-30 ppt. Smooth cordgrass (*Spartina* *alterniflora)* provides a surface for mussel attachment, and the mussels fertilize the plants. Ribbed mussels form dense beds on the edges of salt marshes through waste production, increasing marsh elevation and resistance of the marsh shoreline to erosion, which helps to stem marsh loss. They are an ecological kingpin of the Delaware Estuary. This salt marsh species is valued for its unparalleled benefits to water quality and marsh health.

A top concern for ribbed mussels is habitat loss, since tidal marshes are declining in health and acreage. Tidal marsh area declined by 7% on the New Jersey bay shore between 1996 and 2006 (Kreeger et al. 2011b), and salt marshes are projected to lose 25-50% of their current area under a one meter sea level rise scenario.

4.3.3 Identifying Priority Areas for Marine Bivalve Conservation

For oysters and ribbed mussels, we collected survey data and information about habitat requirements for each species and mapped current and potential ranges within the Delaware Bay and Estuary. We then prepared an inventory of known conservation, enhancement, restoration, and management strategies that have been applied in the Delaware Estuary or other estuaries around the nation. The list of enhancement strategies was pared down to those opportunities that would benefit eastern oysters or ribbed mussels.

Mapping was also a crucial piece of our prioritization approach. We mapped characteristics such as disease zones and New Jersey harvest restriction zones, which could act as constraints in applying different strategies. We also considered the extensive, sustainable management practices of the oyster industry in the Delaware Bay. Conservation and enhancement strategies were then grouped into categories based on physical characteristics, implementation similarities, opportunity, ecological importance, and local knowledge recommendations. Maps for the five types of areas are shown in Section V.

4.4 Delaware Bay Benthic Habitat

Benthic organisms are those that inhabit the sea floor; the name comes from the Greek word “benthos,” meaning “depths of the sea.” We identified and mapped the major benthic habitat types of the Delaware Bay using a range of data sources that describes the bay’s physical features and biological composition. Detailed methods, further discussion of results and data sources can be found in Appendix V of this report.

We defined a benthic habitat as a group of organisms repeatedly found together within a specific benthic environmental setting. To develop a comprehensive map of benthic habitats in the bay, we first mapped the major physical features of the Delaware Bay seafloor, including depth, sediment type, and bottom topography. We then used information on benthic organism distribution, particularly in relation to bottom topography, to delimit a distinct set of environments representing the variety of benthic habitats in the bay. Specifically, three basic steps were followed: 1) quantitative analysis of grab samples to identify distinct and reoccurring assemblages of benthic organisms, 2) recursive partitioning to relate the species assemblages to physical factors (bathymetry, sediment types, geographic location, and seabed topographic forms), and 3) mapping the habitats based on the statistical relationships between the organism groups and the distribution of the physical factors.

Based on data from the Delaware Estuary Benthic Inventory Partnership (246 samples from throughout the bay), the seafloor habitats of the Delaware Bay contain over 300 species in 8 phyla including:

- 106 species of arthropods (crabs, lobsters, shrimp, barnacles)
- 75 species of mollusks (clams, scallops, squid, limpets, sea slugs, snails)
- 130 species of annelids (sea worms)
- 8 species of echinoderms (sea stars, sea urchins, sea cucumbers, sand dollars)
- 5 species of cnidarians (corals, anemones, jellyfish)
- 4 species of chordates (sea squirts)
- 1 species of poriferans (sponges)
- 6 species of nemerteans (ribbon worms)

Based on the bathymetry dataset, the region varied in depth from 0 m at the coast to 47 m along the central trench. The sediment maps indicate that the seafloor is dominated by fine sand, along with large regions of finer silt. Hard bottom substrate is predominately rocky in the upper estuary, while shell areas dominate in the mid- and lower estuary.

We classified the 246 data samples into 20 organism groups based on species composition and abundance. We found that many species groups are restricted to a particular geographic region of the bay, which, based on an examination of the life history of these organisms, is likely due to variation in salinity. Distance from the freshwater upper bay was the single best explanatory variable, followed by bathymetry, grain size, and seabed form.

Two separate but closely related final maps were created. The Ecological Marine Units (EMU) represent all three-way combinations of depth, sediment grain size, and seabed forms based on the ecological thresholds revealed by the benthic organism relationships (Figure 4.14). Benthic Habitats are EMUs clustered into groups that contain the same species assemblage (Figure 4.15). The two terms are not synonymous, but they are based on the same information, and thus, represent two perspectives on the habitat provided by the sea floor. Essentially, the EMU maps show the full diversity of physical factor combinations, regardless of whether a specific habitat type was identified for the combination. The benthic habitat map shows only the combinations of factors, or groups of combinations, for which a benthic organism group was identified. Again, detailed methods and further discussion of results can be found in Appendix V of this report.

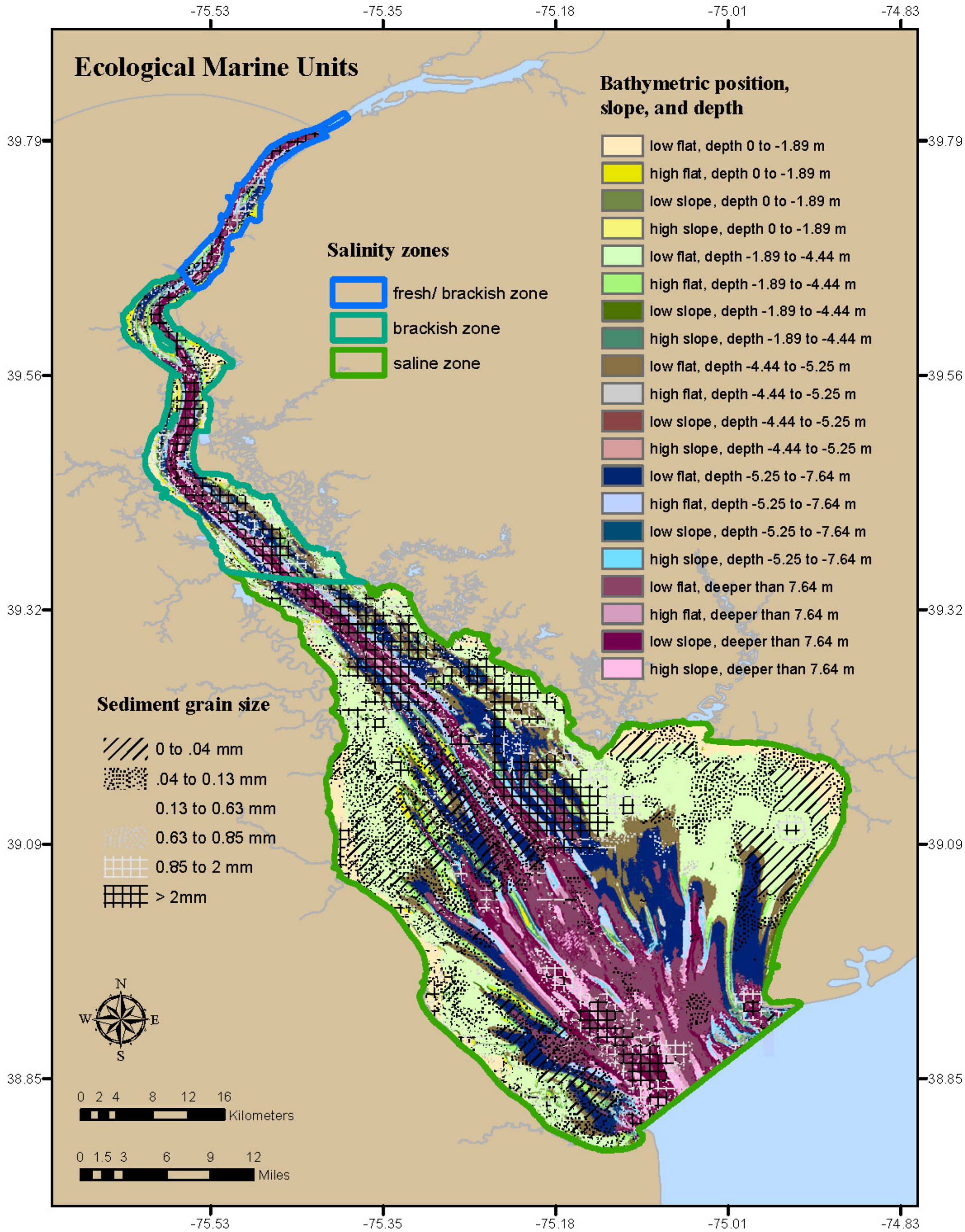


Figure 4.14. Ecological Marine Units of the Delaware Bay

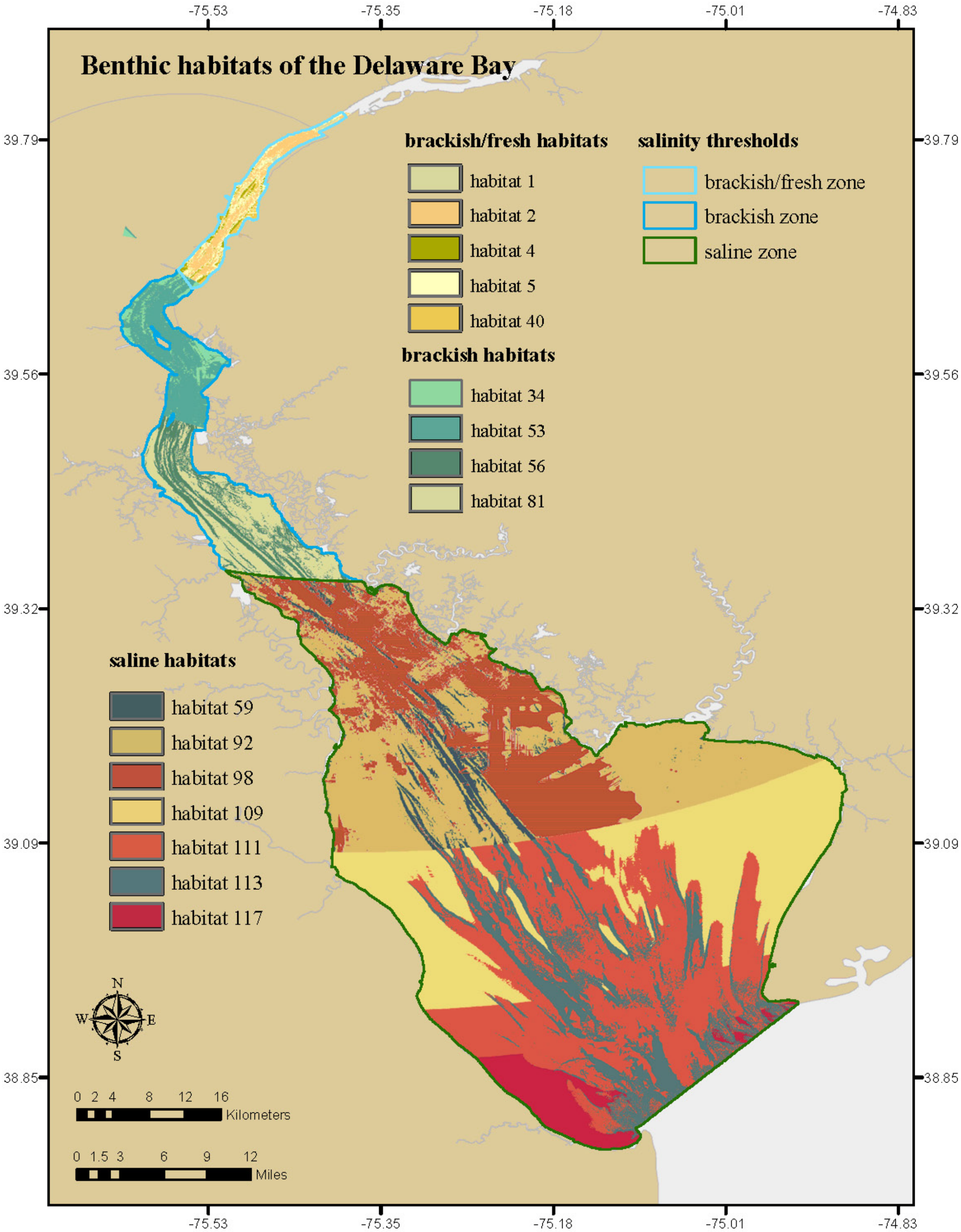


Figure 4.15. Benthic habitats of the Delaware Bay

V. Pulling it All Together: Applying Recommended Conservation Strategies to Identified Priority Areas

5.1 Recommended Conservation Strategies for Freshwater and Tidal Ecosystems

In addition to identifying priority places for conservation, a second and equally important component of this project is to help focus the most appropriate types of protection, restoration, and management actions within these priority places. To do this, we used our ecosystem condition assessment, which highlights attributes of an ecosystem which are likely to be functioning well or may be degraded and in need of restoration. Understanding basic condition of each ecosystem helps identify which conservation actions would be most likely to be beneficial in each priority area to maintain or enhance habitat condition and ecological function that supports biodiversity.

Throughout this section, we use the word *conservation* very broadly to describe any action whose intent is to benefit ecological targets, be it through maintenance, improvement, or enhancement. This includes *protection*, meaning the acquisition or easement of land. This also includes *restoration* or assisting the recovery or resilience of ecosystems that have been degraded, damaged, or destroyed. It may also include ongoing *management* of lands, waters, or fish and other biota, like marine shellfish, to sustain or restore populations or ecological functions. We also recognize that protection, restoration, and management often all have a role at specific places, depending on the combination of ecosystems present, the current condition, and the long-term objectives.

This broad definition of *conservation* encompasses the majority of recommended action categories aimed at our ecosystem targets:

- Forest Conservation
- Non-Tidal Wetland Conservation
- Agricultural Land Protection and Conservation
- Aquatic Connectivity Restoration
- Streamflow Management
- Groundwater/Baseflow Conservation
- Tidal Marsh Restoration
- Shoreline Conservation
- Marsh Room to Move Protection

In this section, we provide some examples of projects that fall within these broad categories. We also highlight some of the existing programs and funding sources that can be used to for implementation.

Forest Conservation

Forest conservation is a critical strategy within the Basin. Not only are forests important habitat in the Delaware Basin in terms of the biodiversity they contain and the ecological functions they serve, but a recent USDA Forest Service report for the Northeastern Area of the United States also emphasizes that the connection of "forest to faucet" is of vital importance to people in the Northeast. Forests are a critical first filter to aid in the protection of drinking water, and managing forests for source water protection is becoming more important as population and water demand increase. Fifteen million people depend upon the Delaware River and headwaters as their primary source of drinking water.

This strategy focuses on the conservation of headwaters areas throughout the basin where large forested tracts remain intact; the protection and/or restoration of floodplain and riparian corridors; and the protection of undeveloped upstream watershed areas in the Coastal Plain to help maintain tidal marsh condition. Forest conservation can be achieved in a number of ways and through a variety of programs and partnerships. For example, forested headwaters can be protected through state and local regulations, through outright fee-acquisition, or by conservation easements. Forests can also be managed through the implementation of public and private forest stewardship plans, or through various certification and management plans. Forests in the basin can also be restored through innovative public-private partnerships, such as the Pinchot Institute for Conservation's Common Waters Fund (sidebar).

Floodplain Forest Community, Upper Delaware River Floodplain
© Gregory Podniesinski

Pinchot Institute's Common Waters Fund

*In February 2011, the Pinchot Institute launched its **Common Waters Fund**, a grant program for private landowners in Pennsylvania, New York, and New Jersey to implement forest conservation practices on their land. The Common Waters Fund will provide incentives to qualifying landowners to implement forest stewardship plans, watershed forestry management practices, and/or conservation easements over the next two years.*

Grants of up to $25,000 are available for eligible landowners, qualified land trusts, and timber harvesting operators to help develop forest stewardship plans; offset the costs of implementing certain forest management practices that will improve forest health and protect water quality; assist with expenses related to placing a conservation easement on a property; and defray the cost of construction, purchase, or rental of portable timber/skid bridges to minimize erosion and sedimentation on streams in priority areas.

More than two dozen partner organizations are part of the Common Waters initiative, including the Delaware River Basin Commission, county conservation districts and planning departments, the National Park Service, and state forestry agencies.

Non-Tidal Wetland Conservation

Basin-wide there is a need for the protection and restoration of non-tidal wetlands. In December 2008, the DRBC's first *State of the Basin Report* noted that over the past 300 years, the Delaware River Basin has lost perhaps 50 percent of its natural marshes. Ranking high in biodiversity, non-tidal wetlands serve as important habitat for many species of wildlife and plants. They also provide a number of other benefits to communities that often go unrecognized, such as helping to control flooding and thereby reducing storm damage, and preventing sediment and pollutants from entering waterways. Consequently, this strategy focuses on the direct protection or restoration of individual forested, scrub-shrub, and emergent headwater and riverine wetlands and surrounding upland buffers.

Acquisition, through fee acquisition or conservation easement, of non-tidal wetlands is a viable strategy to protect non-tidal wetlands in the basin. Wetland laws also regulate the activities that can occur in wetlands; however, regulations do not address the past degradation of wetlands. Restoring non-tidal wetland habitat can take many forms and can occur on public and private lands across the basin.

A number of funding sources are available for restoration and management of wetlands and of wetland buffer areas. One way to implement this conservation strategy is to directly engage private land owners in those areas noted as priorities for non-tidal wetland restoration and protection. Federal funding sources are also available for the protection of important wetlands through fee acquisition or for wetland restoration projects. Habitat improvement achieved through restoration directly benefits key species of concern (sidebar).

Fen Northeast Pennsylvania, Delaware River Basin
© Harold E. Malde

Federal Funding for Wetland Conservation

The U.S. Fish and Wildlife Service's (USFWS) ***North American Wetlands Conservation Act*** *(NAWCA) provides matching grants to non-federal partnerships to carry out wetland conservation projects throughout the U.S. that benefit wetlands-associated migratory birds. NAWCA projects also benefit other fish and wildlife species, including rare, threatened, and endangered species that are dependent on wetlands ecosystems.*

The conservation non-profit group, ***Ducks Unlimited****, has led projects throughout the Delaware River Basin to protect migratory birds along the Atlantic Coast Flyway. Projects include on-the ground wetland conservation projects as well as research on migratory species, such as exploring the decline of black duck populations along the Atlantic Flyway.*

The protection of key wetland habitats can also be funded through the ***Land and Water Conservation Fund****, which provides matching grants for land acquisition. In October 2010, LWCF funds were used to fund the initial land purchase for the* ***Cherry Valley National Wildlife Refuge****, which will grow to encompass more than 20,000 acres near the Delaware Water Gap. Cherry Valley is home to 85 rare species, including the federally threatened bog turtle.*

Agricultural Land Protection and Conservation

Farming has occurred throughout human history in the Delaware River Basin and, in some areas, agricultural practices continue to be a dominant influence. Well-managed farms provide environmental benefits including wildlife habitat and the potential for groundwater recharge. While the continuation of agriculture in the basin is critical for the culture and economy of the region, conservation projects that can take place on current and former agricultural lands would benefit the aquatic resources and the people of the basin. In the estuary, agricultural lands adjacent to tidal marshes need to be preserved and managed to allow for the natural migration of tidal marshes as sea levels rise. Restoring old agricultural fields to forests improves water quality and reduces flooding potential in vulnerable areas. Protecting and managing agricultural lands can help us both conserve aquatic resources in the basin and maintain the rural, working landscape that is an important part of the Delaware River Basin.

This strategy focuses both on the protection and best management of current agricultural lands for ecological value. The four Basin states already have programs that promote and fund the protection of agricultural lands primarily through land purchase from willing sellers either in fee or by conservation easements. These programs serve several purposes that range from preserving a land base in order to support and sustain agricultural operations to protecting rural landscapes. This strategy also includes conservation activities such as the restoration of retired agricultural areas in floodplains or the compatible management of agricultural lands in the floodplain to allow for episodic flood storage while still meeting the needs of active agricultural production.

Recently a number of environmental NGOs have recognized the value of partnering with the agricultural community to advance conservation interests (sidebar). This conservation strategy is tailor-made for implementation by U.S. Department of Agriculture (USDA), its Farm Services Administration (FSA), Natural Resources Conservation Service (NRCS), and local conservation districts through its Farm Bill-authorized programs.

U.S. Farm Bill

*A recent report authored by a coalition of conservation groups, **Conserving Habitat Through the Federal Farm Bill: A Guide for Land Trusts and Landowners**, states that the federal Farm Bill is the greatest source of private land conservation funding in the United States.*

*Through Farm Bill funding, landowners can plant trees to improve water quality; access financial assistance through **Environmental Quality Incentive Programs (EQIP)** to achieve and implement conservation practices on their land; participate in the wildlife habitat incentive program (WHIP) and obtain cost share funding to assist with the implementation of wildlife habitat development practices. Landowners can also access a voluntary **Wetland Reserve Program (WRP)** to enable them to establish conservation easements on wetlands on their property as well as funding for 100% of the wetland restoration costs.*

NRCS has identified targeted watersheds in the basin that they consider priorities. Where these priorities overlap, conservation NGOs and funders should build upon existing Farm Bill conservation programs and develop additional incentives that are attractive to private landowners to undertake projects that support the protection and restoration of biodiversity on their lands.

Aquatic Connectivity Restoration

Free-flowing rivers provide uninterrupted habitat for fish and aquatic wildlife, clean water for drinking, and recreational opportunities for many people. A history of dam-building has left some of the Delaware's tributaries fragmented and suffering the impacts of altered patterns of water flow and downstream transport of sediments and nutrients. These stream alterations have reduced fish populations by blocking fish movement up and downstream, leading to decreased fishing opportunities. They also have negatively affected water quality and recreational opportunities like swimming and kayaking. Downstream marshes also may be more vulnerable to sea level rise where they are not receiving as much sediment from rivers upstream as they did before dam construction. Fortunately, as awareness grows of the benefits of removing defunct dams, an increasing number of opportunities to restore connectivity of the Delaware River's tributaries will become feasible.

The aquatic connectivity restoration strategy applies to headwaters, tributaries, floodplains, and tidal marshes that have been fragmented by dams, culverts, and other structures that block access to habitat or constrict flow. This strategy aims to improve access and passage for fish and other aquatic organisms and to move, remove, or alter the operations of infrastructure that blocks or constricts natural tidal flow of coastal rivers. In recent years in the Delaware Basin, aquatic connectivity restoration has gained momentum. A few examples include multiple dam removals on the Schuylkill and Musconetcong Rivers, and dam removal feasibility studies on the Brandywine and Lehigh Rivers.

All of these efforts have involved multiple partners, including federal agencies like the U.S. Fish and Wildlife Service, the U.S. Army Corps of Engineers, National Oceanic and Atmospheric Administration, and the Natural Resource Conservation Service; state agencies including the Pennsylvania Fish and Boat Commission, Pennsylvania Department of Environmental Protection and New Jersey Department of Environmental Protection; and non-profit organizations such as Trout Unlimited, American Rivers, Delaware River Keeper, and the Musconetcong Watershed Association.

American Rivers and the National Oceanic and Atmospheric Administration (NOAA) Community-Based Restoration Program

*For over ten years, **American Rivers** and **NOAA** have maintained a grants program to support barrier removal projects for diadromous fish, those species that migrate between saltwater and freshwater in order to complete their lifecycle. The program funded over 120 restoration projects in its first nine years and now supports projects along both the Atlantic and Pacific Coasts of the U.S. Grants can be used to complete feasibility analyses for restoration projects, as well as the engineering designs and actual construction phases of a project.*

In addition to financial support, NOAA and American Rivers also offer technical assistance, such as advice on project design, finding matching funds and contractors, staying within compliance of permits, and engaging the local community.

Streamflow Conservation

Natural variations in seasonal streamflow are critical for sustaining healthy riverine and floodplain systems. However, the Delaware River Basin Commission (DRBC) report, Water Resources Program FY 2010-2015, notes that "Water supply planning in the basin generally has not taken into account the instream flow needs of aquatic communities. Recent reviews of several DRBC water supply dockets indicate that flows in some surface waters could be substantially impacted should withdrawals increase to current allocation limits. While scientific investigation continues across the basin to determine the flow needs of aquatic communities, changes to current allocations or the application of permit conditions may be warranted to maintain adequate flows in the tributaries and the River."

Streamflow in the basin is affected by surface and groundwater withdrawals and releases from reservoirs built for water supply, energy production, flood control, and recreation purposes. The basin states, DRBC, and New York City have over 50 years of history of joint water management of the three Upper Delaware reservoirs that are part of New York City's water supply system. Releases from these and other basin reservoirs are made to address downstream considerations, including stream temperature, salinity in the lower river, and downstream water demand. In addition to reservoir management, individual and cumulative water withdrawals that are of sufficient magnitude relative to the source stream can cause impacts to aquatic resources.

Ecologically-based streamflow management requires assessments of water availability, current water use, and an understanding of how aquatic species respond to changes in streamflow. Natural resource agencies within the basin, including DRBC, US Geological Survey, and state natural resource and regulatory agencies have expressed a clear desire for an approach to evaluating the impacts of flow alteration on aquatic resources that is applicable within the basin and throughout the basin states. The development and application of "instream flow" or "environmental flow" criteria is central to this goal. These criteria can provide a basis for managing water withdrawals and reservoir releases by defining the acceptable levels of flow alteration that still allow aquatic resource goals to be met.

WATERSMART

*In 2011, through the U.S. Bureau of Reclamation's **WaterSMART Program**, the U.S. Geological Survey (USGS) will be initiating a study of Delaware River Basin issues related to water use and availability as one of three national pilot basins. Issues such as the impact of land-use change on nutrient loading and water quality, climate change and sea-level rise impacts on water supply, and increased water withdrawals and their impact on water availability or ecologically sustainable flows, have been identified for potential consideration within this study.*

USGS will develop and implement the study plan in coordination with DRBC and other natural resource and regulatory agencies and stakeholders. The Delaware study is expected to take three years and USGS researchers will be funded at about $500,000 for each of those years to conduct the studies.

Riverine Scour and Shrubland Community in Upper Delaware Floodplain © Gregory Podniesinski

Ⓖ Baseflow/Groundwater Conservation

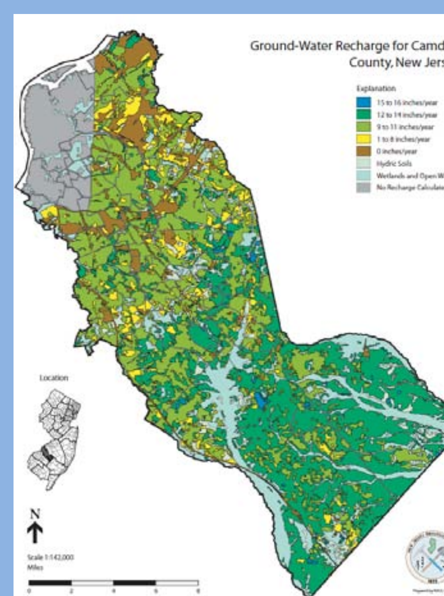
The Delaware River Basin's groundwater resources provide vast amounts of water for natural ecosystems and human use every day. Shallow aquifers help keep streams running and prevent wetlands from drying out—this function is particularly important in the Coastal Plain, where baseflow (groundwater that flows at the surface) accounts for approximately 90% of total streamflow. Many communities and rural residents throughout the basin are completely dependent upon groundwater for their drinking water. Though this resource is not readily visible, it needs to be conserved; groundwater depletion, caused by excessive withdrawals in the Coastal Plain, has already caused saltwater contamination in areas where freshwater aquifer levels have dropped significantly.

This strategy focuses on the conservation of headwaters where groundwater availability is high and use is low. It targets headwaters that are predominantly in natural cover with limited industrial, commercial, and agricultural groundwater use. In some of these areas where groundwater-dependent ecosystems like wetlands are particularly abundant there are opportunities to keep ecosystems functioning by conserving those intact forests, maintaining recharge into aquifers, and limiting input of contaminants. In other areas of the basin, groundwater conservation can be more challenging due to high demands.

Several agencies are working to protect water supplies in these areas and across the basin. For example, the DRBC has established ground water protection areas with special regulations, the U.S. Geological Survey has studied water demands and projected supply scenarios, and the New Jersey Geological Survey has mapped recharge rates for the whole state. Some of New Jersey's efforts to help protect and restore groundwater resources through funding sources that can target identified areas of high recharge value are highlighted (sidebar).

New Jersey's Natural Resource Restoration Program Initiative

Dating back to the early 1990s, New Jersey has had a program in place to collect funds for damages to natural resources to be applied to "replacement" restoration and protection efforts. Groundwater has always been a target of this program, which is currently called the ***Natural Resource Restoration program****. Funding through this program is available for acquisition of land to protect or restore aquifer recharge. Protecting high recharge areas is one way to help ensure plentiful and clean groundwater supplies for people and nature. About 40% of the state's drinking water comes from groundwater.*



NJ Geologic Survey map of recharge rates in Camden County, NJ, in inches per year

Tidal Marsh Restoration

Tidal marshes are the characteristic feature of the Delaware Estuary, providing habitat for wildlife and ecosystem services to the people of the region. However, the State of the Basin report notes that, over the past 300 years, the Delaware River Basin has lost perhaps 50 percent of its natural marshes and that perhaps only five percent of pre-settlement tidal freshwater marshes remain. And as climate change brings about sea level rise and salinity changes in the estuary, new threats have emerged to tidal marshes and to the human communities that lie adjacent to them. To continue to provide the important services to people and nature, restoration of degraded and vulnerable freshwater and saltwater/brackish tidal marshes is an important strategy in the Delaware River Basin.

Tidal marsh restoration conservation strategies are recommended for vulnerable brackish and salt marshes with relatively low elevation compared to the surrounding marshes or for those that have been severely altered. Freshwater tidal marshes in the urban corridor between Wilmington, DE and Trenton, NJ are the largest complexes remaining on the East Coast; however, habitat conversion has led to severe losses. Strategies are recommended for freshwater tidal marshes where their restoration could improve water quality and increase wildlife habitat in a heavily urbanized landscape.

Restoration activities may range from small-scale living shorelines projects in tidal creeks to large-scale sediment management on marsh surfaces. These activities can be carried out by non-profit organizations and state and federal agencies, many that are part of the Estuary Restoration Act's interagency Council (sidebar). One example of large-scale restoration in the Delaware Bay began in the 1990s when Public Service Enterprise Group (PSEG) purchased and restored over 20,000 acres of former salt hay farm marshes and *Phragmites australis*-dominated tidal marsh and adjacent uplands to mitigate for fish intakes at their cooling towers in Salem, NJ.

The Estuary Restoration Act

*The **Estuary Restoration Act** was established to "encourage the restoration of estuary habitat through more efficient project financing and enhancing coordination of Federal and non-Federal restoration programs."*

Through an interagency council established by the Estuary Restoration Act, NOAA, U.S. Fish and Wildlife Service, the Environmental Protection Agency, and the U.S. Army are working together to carry out the act's directives of promoting a coordinated Federal approach to estuary restoration, forging effective partnerships between public and private sectors, providing financial assistance, and developing monitoring and research capabilities.

Funding through the Council can be obtained from NOAA Fisheries. Projects must address the directives set forth by the Council and support the Council's Estuary Habitat Restoration Strategy. Priority is given to projects that address climate change impacts, occur in watersheds where other beneficial habitat projects are ongoing, and demonstrate innovative technologies or approaches to estuary restoration.

Shoreline Conservation

Natural gently sloped, low energy shorelines along the Delaware Bay provide spawning grounds for horseshoe crabs and critical feeding opportunities for migratory shorebirds. Shorelines also protect tidal marshes and allow for the natural movement of marshes as sea levels rise in the brackish/salt and freshwater tidal marshes of the estuary.

Many Delaware Bay shorelines are free from infrastructure and are currently protected; however, protecting natural shorelines that are not currently held in conservation, through land acquisition and conservation easements, is recommended in the Delaware Bay and estuary regions of the basin. There are also opportunities to restore degraded and eroded shorelines. For example, remnants of old coastal towns are scattered across the bay's shorelines and are in need of restoration. In many circumstances, healthy natural systems are required to protect human communities behind the shorelines as sea levels rise and storms cause damage to natural and human communities. In conjunction with tidal marsh restoration strategies, shoreline conservation addresses the threats to our coastal habitats and adjacent human communities.

Acquisition of undeveloped natural beaches can be accomplished by state or federal agencies, as well as non-governmental conservation organizations. The New Jersey Department of Environmental Protection, Delaware Department of Natural Resources and Environmental Control, U.S. Fish and Wildlife Service, The Nature Conservancy, Natural Lands Trust, and other environmental NGOs own and manage natural Delaware Bay beaches.

Thompson's Beach, New Jersey
© TNC staff

The National Coastal Wetlands Conservation Grant Program

While there is no direct funding source for shoreline conservation, funding to acquire undeveloped natural beaches or for beach restoration is available through a variety of state or federal agencies, the U.S. Fish and Wildlife Service and the U.S. Army Corps of Engineers. For example, the U.S Fish and Wildlife Service's ***National Coastal Wetlands Conservation Grant Program*** *was established by the Coastal Wetlands Planning, Protection, and Restoration Act in 1990. Annually the U.S. Fish and Wildlife Service provides between $18 and $21 million in matching grant money to coastal states for conservation projects, including acquisition, restoration, enhancement, and management of coastal wetlands throughout the United States.*

Coastal Wetlands Program funds encourage partnerships, support watershed planning, and leverage on-going projects to maximize the benefits of limited funding.

In addition, throughout the Delaware Bay, reach restoration work is carried out through New Jersey DEP's Bureau of Coastal Engineering and Delaware Department of Natural Resources & Environmental Control (DNREC) Division of Soil and Water Conservation. In Delaware, the Division of Soil and Water Conservation's Shoreline and Waterway Management section regulates coastal construction in beach areas and protects and enhances Delaware's beaches.

Marsh Room-to-Move Protection

The tidal marshes of the Delaware Bay provide food and habitat for a wide range of plants and animals that are important to the aquatic biodiversity of the Delaware Basin. These marshes are a critical link in the estuary's food web and are an important nursery ground for a number of recreationally and commercially important coastal fish species, crabs, and other crustaceans. These marshes are also vitally important in protecting coastal areas from flooding and storm surges. The tidal marshes of the Delaware Bay support a wide range of recreational activities including hunting, fishing, and wildlife viewing.

These marshes are now being threatened by sea level rise, currently projected to be up to 10mm per year over the next century (Kreeger et al. 2010). Tidal marshes are able to respond to sea level rise in two ways. They can accrete inorganic and organic sediment, thereby increasing elevation to keep pace with sea level rise, or they can migrate inland over natural lands with gentle slope and elevation. To allow for this natural process to occur, the protection of natural lands adjacent to tidal marshes, through land acquisition or conservation easements, is a recommended conservation strategy in the bay and estuary regions of the basin. Wise management of lands adjacent to tidal marshes can assist in the migration of tidal marshes inland.

Allowing for marsh migration is a relatively recent conservation strategy that is being evaluated by a number of coastal states. In order to increase the accuracy of tidal marsh migration predictions, additional data collection and analysis by both the states of New Jersey and Delaware will be required. Delaware currently has a project underway to do just this. The highlighted example to the right suggests a way to incorporate the map products in this report and the conservation strategy of providing marshes "room to move" into the State's adaptation planning.

Protection of marsh room-to-move lands can be carried out by U.S. Fish and Wildlife Service, New Jersey Department of Environmental Protection, Delaware Department of Natural Resources and Conservation, and conservation non-profit organizations, such as The Nature Conservancy, Natural Lands Trust, and the New Jersey Conservation Foundation.

Delaware and Sea Level Rise

*The **State of Delaware's Coastal Programs** office has established a Sea Level Rise Advisory Committee that is comprised of a representative from each State of Delaware Cabinet Department and representatives from municipal government, business advocacy organizations, and citizen advocacy organizations. This group is charged with helping develop an Adaptation Plan that recommends a wide-range of potential solutions to reduce risk of sea level rise impacts.*

*The nexus between Delaware's efforts to address and plan for the impacts of sea level rise and this report is clear. As the state moves forward to implement its Adaptation Strategy, this project's "**marsh room-to-move protection**" approach can be easily incorporated. For example, once the state completes its tidal marsh vulnerability assessment for its Adaptation Plan, the assessment can be easily compared to this project's tidal wetlands priority protection and restoration areas for aquatic biodiversity. It is anticipated that the overlap will be considerable especially in places that the state has already identified as priorities in its **Coastal and Estuarine Land Conservation Program** (CELCP) plan. That program, established by Congress to provide matching funds to acquire coastal and estuarine lands or interests therein for permanent protection if applied strategically, can be used to implement a marsh room to move strategy.*

5.2 Recommended Conservation Strategies for Marine Bivalve Habitats

The next two conservation strategies offer an array of actions to conserve oysters and ribbed mussels in the Delaware Estuary. Traditional shellfish restoration tactics are presented as well as new and experimental options. Bivalve shellfish restoration and management must be grounded in existing ecological and management paradigms; therefore, we discuss policy impediments and restrictions that might slow implementation of best current and future measures. In addition, conservation strategies for bivalves should be revisited every few years as new information develops.

Bivalve shellfish habitats can be enhanced through protection, restoration, and other management actions. Since conservation strategies are species-specific, the best tactic will therefore depend on conservation and/or management goals and the targeted bivalve species. The implementation of any of the oyster conservation strategies must work in concert with these existing management groups in order to achieve full success. Please refer to the full PDE shellfish priorities report for more background, discussion, and references regarding conservation priorities for marine bivalve shellfish (Kreeger et al 2011a).

Shellfish Restoration

This strategy focuses on methods to restore or create new populations of shellfish in the Delaware Bay.

EXAMPLE ACTIONS:

SP *Shell Planting*: Strategic shell planting is a top recommended conservation tactic for oysters, because it has been the most effective tactic for boosting oyster production in the Delaware Estuary (see, for example, the Delaware Bay Oyster Restoration Project (PDE 2007), and because it is highly cost-effective. Funding and project management for shell planting has been overseen by an Oyster Restoration Task Force comprised of agency, industry, non-profit, and academic partners from Delaware and New Jersey. Sites for shell planting are selected based upon existing or historic oyster setting patterns, reef habitats, and the most recent monitoring data. When oyster larvae are most abundant in the water (late June to early July), targeted reefs are planted with clam and oyster shell, providing hard substrate to which oyster larvae attach. The new recruits (spat) remain on these beds. Sustained significant funding for shell planting is critically needed. To sustain a positive shell budget, stabilize and enhance oyster stocks, and ensure a continued commercial industry, the task force estimates that an annual shell planting budget of $1 million is needed.

DS *Designed Shellfish Reef:* Vertical reefs can be used to create more surface area in the water column to attract spat and build more multi-dimensional oyster reefs. One example of a vertical reef involves using a cage device. Shell is placed inside the cage (probably made of metal). The holes of the cage are large enough to attract new larvae to colonize on the shell inside, but small enough to prevent poaching. Over time animals will settle on top of animals, until the cage structure will completely disappear into the new reef. For shallow areas, a variety of commercial reef construction products are also now available. "Reef-Blok" and "Wave Attenuation Devices" are other commercial products that have been shown to be effective in areas along the Gulf of Mexico

(The Reef Ball Foundation 2011). In order to test artificial reefs, pilot projects could be developed as part of living shoreline projects or in tributary areas, and later potentially expanded to other shallow marginal areas.

Gardening: Gardening refers to any small scale activity which grows shellfish on a temporary non-reef structure. Shellfish gardens are often used to promote conservation through community participation by schools, parks, businesses, watershed groups, and waterfront property owners (VDEQ 2010). The PORTS program in New Jersey (seen in maps of Areas 2 &3) successfully incorporated some forms of oyster gardening concepts in earlier programs to educate school children about oyster restoration. In Delaware Bay, the major constraint on oyster gardening is the human health risk associated with consumption of oysters grown in poor quality waters. New Jersey recently banned gardening of any commercial species in tributaries and other closed waters because of sanitation concerns. The New Jersey ban does not apply to ribbed mussel gardening because they are not a commercial species; therefore, shellfish gardening methods should be developed for ribbed mussels.

Living Shorelines – Intertidal Zones: Living shorelines are shoreline stabilization projects that can be used to offset wave energy and sea level rise effects while also enhancing ecological values. They range in complexity from modest biological modifications in low energy areas to hard structures in high energy areas. The Delaware Estuary Living Shorelines Initiative (DELSI), piloted in New Jersey salt marshes, was intended to stabilize eroding tidal marsh shorelines in low to moderate energy areas, partly by the binding action of ribbed mussels and plants within fibrous logs and mats and shell bag treatments. This method bolstered the resilience of marsh plants by stabilizing erosion while also encouraging recruitment of shellfish communities. In addition to these benefits, fish and wildlife use the mussel-rich edges of salt marshes. Shellfish-based living shorelines could be expanded as a tactic to both promote bivalve populations and to stabilize coastal habitats such as tidal wetlands.

Living Shorelines – Subtidal Breakwater: Near-shore oyster breakwaters in shallow subtidal areas may help to stem shoreline erosion and prevent flooding for coastal properties, especially when combined with intertidal living shorelines and hybrid arrangements. Potential options for nearshore oyster breakwaters in Delaware Bay include places where historic reefs existed in shallow nearshore areas and places where the current habitat is marginal for tonging or dredging (too shallow or rocky). Reef balls, reef block, or other materials can be used to create nearshore reefs as breakwaters. Success of this tactic depends on wave energy, bottom type, navigation conflicts, and the fit with area management goals. We recommend that pilot oyster breakwater projects be completed, which could be expanded or replicated if successful. Pilot projects might be more easily permitted within the State of Delaware than in New Jersey, allowing for demonstration sites to build awareness.

Shellfish management

This strategy focuses on the many ways to affect the management of shellfish (primarily oyster) resources in the Delaware Bay.

<u>EXAMPLE ACTIONS</u>:

HG *Harvest Guidelines:* Due to the long track record of successful stock maintenance and an adaptive and proactive management structure, the Delaware Bay oyster fishery has been declared "sustainable" according to the Stock Assessment Review Committee (SARC). Harvest should remain at sustainable levels, and any changes to oyster harvest guidelines to improve management should be made in concert with the SARC and vested parties, and with careful consideration of the socio-historical and economic importance of oysters. Ribbed mussels are not commercially or recreationally harvested; therefore, no harvest guidelines are recommended.

SM *Special Management Areas:* Special management areas (SMAs) are manipulation-free sanctuaries for aquatic life, designed to preserve aquatic biodiversity and native ecology (Edgar et al. 2007). In the Delaware Estuary, no formal SMAs have been established to restrict oyster harvesting, although harvest is prohibited in certain waters because of shellfish sanitation concerns. We recommend three types of special *oyster* management areas (SOMAs) in the Estuary:
1) Marginal beds which are shallow and unsuitable for oyster boats to navigate, including areas where no reefs currently exist but where future reefs might become established, such as the area around the C&D Canal (see Area 4). 2) Areas where more monitoring and study need take place on the upper oyster beds (Liston Range, Hope Creek, Fishing Creek), or where oysters are moved to replenish other beds down bay following harvest and natural mortality. 3) Tributary rivers, which are closed to harvest and present opportunities for habitat expansion as sea levels rise and tributary embayments widen.

Two types of special management areas are possible for the *ribbed mussel*: habitat preservation and scientific study. Despite protections under the Clean Water Act, salt marshes (and ribbed mussels) are still being lost due to erosion and sea level rise (Kraeuter and Kreeger 2010). Implementation of erosion control projects would buy more time for the inland migration of these habitats, thereby helping to preserve ribbed mussels and their numerous ecosystem benefits (Kreeger and Kraeuter 2010). More study is recommended to understand the life history, ecology, and habitat requirements of ribbed mussels so that desired outcomes from shellfish enhancement efforts can be maximized.

HS *Hatchery/Seed Production/Population Augmentation:* Hatcheries throughout Delaware Bay can be used not only to boost shellfish populations for harvest, but also to support ecological restoration of depleted stocks, especially when natural recruitment is low. Hatcheries can also be used to breed disease-resistant oysters that are more resilient to salinity rise from climate change (see Area 4). Some hatchery and aquaculture facilities in the bay are currently run by Rutgers

University, and there are several small commercial hatcheries along the Atlantic Coast. The University of Delaware also maintains a small research hatchery in Lewes. .

Spat Collection & Relaying: Relaying, the process of transplanting live bivalves to a new location, has been used as an oyster management technique for centuries. Relaying of spat (baby oyster) and adults currently occurs in Delaware Bay on the upper seed beds. In the lower portion of the bay, spat recruitment is high, but survival is low because mortality from predation, disease and sedimentation is high in the higher salinities. A proven tactic is to put shell out to catch spat, and then move the shell and settled spat to lower disease zones to mature. This strategy was successfully used as part of the Delaware Bay shell planting project where spat were collected on shell placed in the NJ Cape Shore area. Methods for collecting natural recruitment of ribbed mussels have yet to be developed. Lower bay spat collection and relaying should continue as a means to replenish and expand the populations harvested by commercial oystermen. We also recommend research to develop methods for collecting natural recruitment of ribbed mussels.

Extensive Aquaculture: Extensive aquaculture refers to cultivation that exerts relatively limited control of the cultivated organism, and is often carried out in natural waters rather than tanks. The oyster fishery is arguably a form of extensive aquaculture given the level of manipulation of the organism, which includes transplanting oysters from upper to lower seedbeds, planting shell to improve bottom habitats for oyster recruitment and relaying spat from the lower bay. Extensive aquaculture should be permitted where supported by the market. Successful aquaculture enterprises should be encouraged rather than discouraged with unjustified barriers. Although aquaculture is not an enhancement priority, it will have enhancement benefits, so a "do not hinder" approach is recommended.

Intensive Aquaculture: Intensive aquaculture, involving much more control of the organisms' life cycle, may include hatchery production, a nursery phase, and cage or bag culture during grow out. The recommendation here is similar for Extensive Aquaculture above: do not hinder as long as siting for intensive aquaculture is selected to ensure any environmental effects are negligible or beneficial.

Promote Disease Resistance: The oyster diseases MSX and Dermo are two primary factors limiting oyster populations in Delaware Bay. Salinity largely determines disease levels and distribution, hence the management of freshwater inputs from the upper watershed is a high priority for oyster health. Development of disease-resistant stocks can be achieved through aquaculture and oyster gardening. In Delaware Bay, data from the Haskin Shellfish Research Laboratory indicate that the native oyster population has become MSX-resistant through natural selection (Ford and Bushek in prep). Unfortunately, resistance to Dermo has yet to be developed despite extensive experimental breeding programs. For this reason, there is a critical need to support more research on Dermo disease.

Potential funding sources for Shellfish Management and Restoration

- *Federal Agencies*. Through an appropriation to the Army Corps of Engineers, $5 million was directed to oyster shell planting between 2005 and 2010, resulting in up to 50-fold increases in spat recruitment on planted areas and a net positive, bay-wide shell budget by 2010. Grants from the National Science Foundation, NOAA Sea Grant, and Army Corps of Engineers also have supported various scientific studies on bivalve shellfish that benefit managers and conservation planners.

- *State Agencies*. The States of Delaware and New Jersey, and the interstate Delaware River Basin Commission, have provided both financial and staff support for shell planting by the Delaware Bay Oyster Restoration Task Force. State environmental agencies also undertake or support important shellfish sanitation and water quality monitoring.

- *Non-Governmental Organizations.* Entities such as the National Fish and Wildlife Foundation, Partnership for the Delaware Estuary (PDE), American Littoral Society, and The Nature Conservancy have provided grants, in kind resources, or staff to facilitate the restoration, monitoring, and scientific study of bivalve populations. In addition to funding oyster projects, these groups have recently been active in developing living shoreline tactics that promote other species such as ribbed mussels.

- *Oyster Industry.* Commercial oystermen have traditionally recognized the importance of sustaining shell budgets and managing stocks to both boost harvests and ensure long-term sustainability. This culture of self-policing and reinvestment continues today as evidenced by the industry's active support for scientific monitoring, area management, and self-taxing for cultch fund contributions.

- *Other Industries.* Numerous companies that operate within the Delaware Estuary and its watershed have often provided support for conservation of various natural resources, including bivalves. For example, the DuPont Clear into the Future program has supported scientific research on oyster diseases and recently contributed to the shell planting effort. PSEG has supported research on the role of ribbed mussels in sustaining salt marsh health.

- *Academic Institutions.* Numerous regional universities, most notably the Rutgers Haskin Shellfish Research Laboratory, have provided in-kind support, staff, and students to perform critical monitoring and scientific study of the area's bivalve resources.

5.3 Priority Conservation Area Maps and Recommended Strategies

The resulting priority areas and recommended conservation strategies are presented in a series of sub-basin packages. Each package includes:

- A map with the identified priority conservation areas within the sub-basin and the broad recommended conservation strategies – described in the previous section – applied to watersheds within that sub-basin.

- A general ecological description of each sub-basin and outline some of the projects and partners that are currently working on these conservation strategies.
- Additional maps for each sub-basin that depict land use, protected lands, and the identified priority areas displayed by ecosystem type in each of the sub-basins.

For marine bivalve habitat, five conservation strategy areas have been identified and appear in maps labeled *Area 1 – High Productivity Oyster Beds*, *Area 2 – Marginal (harvest) Areas*, *Area 3 – Hybrid Oyster-Mussel Areas*, *Area 4 – Climate Future Targets*, and *Area 5 – Ribbed Mussel Target Areas*. Each map is accompanied by a table explaining the recommended strategies for each area. The strategies also appear directly on each map. These strategies are not limited to the five types of target areas and can be applied more broadly across the Delaware Estuary. Future iterations of this study are expected to yield additional target areas and new restoration tactics. The five maps presented in this report provide examples of the best areas for implementation of highest priority tactics based on best current knowledge.

The Upper Delaware River:

Priority Conservation Areas and Strategies

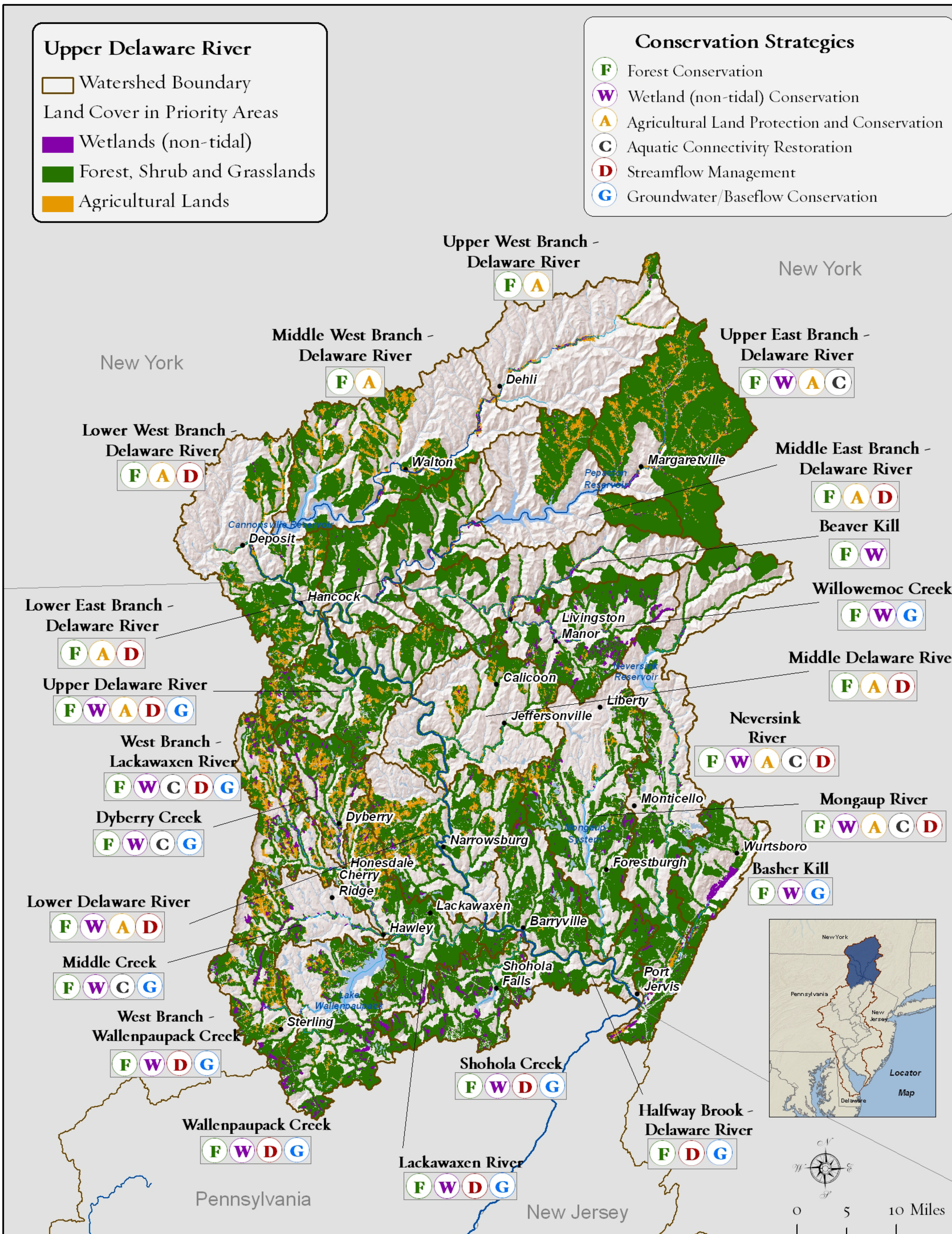


Figure 5.1. Priority Conservation areas and recommended conservation strategies in the Upper Delaware River

The Upper Delaware River

The Upper Delaware River ~ The Upper Delaware River, including the Neversink-Mongaup, East-West Branch, and the Lackawaxen sub-basins, extends 77 miles from Hancock, NY to Port Jervis, NY and Matamoras, PA. Draining an area of approximately 3,500 square miles, this area is located in the Appalachian Plateau physiographic province, specifically the Glaciated Pocono Plateau and the Catskill Sections. Elevation ranges from nearly 4,200 feet at Slide Mountain in the Catskills to 400 feet at Port Jervis, NY and Matamoras, PA.

By the 1800s, industry and commerce were booming in the area due to the construction of the Delaware and Hudson Canal, which brought coal to New York City from eastern Pennsylvania. The second heyday for the Upper Delaware was tourist-driven, as the Catskills were a popular vacation spot from the 1920s through the 1960s. In many communities on the NY side of the basin, aging resorts and bungalow communities persist today. The Pocono Mountains are still a very popular vacation destination; Pike and Wayne Counties (PA) are the most rapidly growing areas within the basin.

Several large dams were constructed on major tributaries in the early to mid-1900s to provide water and electricity for nearby populations. These include three large reservoirs on the Neversink and the East and West branches of the Delaware River that supply drinking water to New York City. In 1926 Pennsylvania Power and Light built a hydroelectric dam on Wallenpaupack Creek, a major tributary of the Lackawaxen River. These reservoirs have caused a significant reduction in streamflow and have altered the natural flow regime, impacting aquatic communities. Over the past decade considerable progress has been made in managing the NYC reservoirs to balance the need to protect drinking water with the needs of aquatic life downstream.

Today this upper portion of the Delaware River basin is mostly forested, with a few small towns/cities dotting the landscape (Figure 5.2). Recreation, tourism, and natural resource management and extraction are the primary drivers of the economy. The Upper Delaware River is a designated National Wild and Scenic River for 73 miles from just north of Port Jervis to Hancock, NY. Significant portions of the watershed are in protected status, and water quality is considered some of the best on the East Coast (Figure 5.3).

Eastern Brook Trout ~

Eastern Brook trout (*Salvelinus fontinalis*) are an iconic species in the Upper Delaware. Theodore Gordon, considered the father of modern American fly fishing, perfected his dry-fly techniques on the Neversink River in the 1800s, and fisherman flocked to the Catskills and Poconos to fish for the native brook trout. Today, as a result of competition with introduced brown and rainbow trout, habitat destruction, sedimentation, acid rain, and increased water temperatures, brook trout populations are just shadows of their former glory (EBTJV 2006). The Eastern Brook Trout Joint Venture prioritizes brook trout strongholds in tributaries to the Delaware River in New Jersey, Pennsylvania, and New York. In light of climate change and other persistent threats, it is critical to prevent the loss of populations that contribute to the overall genetic variation in the basin. Watersheds with naturally reproducing brook trout, including the **Beaverkill** and **Willowemoc** (NY), should receive the highest priority for protection and restoration (TU 2009).

Conservation Highlights ~

The map on the reverse (Figure 5.1) highlights watersheds within the Upper Delaware River Basin where **Forest Conservation, Wetland Conservation, Agricultural Land Protection and Conservation, Aquatic Connectivity Restoration, Streamflow Management,** and **Groundwater/Baseflow Conservation** strategies would help protect and restore basin biodiversity. In addition, Figure 5.4 illustrates the identified priority conservation areas within this region by ecosystem type, without associated land cover. Specific conservation strategy examples include:

Forest Conservation: Headwaters

In the headwaters of the Upper Delaware, forest conservation is a priority conservation strategy. Several large unfragmented forested areas provide cores for expanding headwater conservation, especially in the **Neversink**, **Beaverkill**, **Willowemoc**, **East Branch**, and **Shohola watersheds**. In this region, several funds and programs are available to help landowners protect forested headwaters. For example, the *Common Waters Fund* provides funding to support the development of forest stewardship plans, to implement forest management practices, and for conservation easements. For lands within the New York City watershed, the *NYC Department of Environmental Protection's Land Acquisition Program* protects lands either through fee simple acquisition or conservation easement. In addition, The Nature Conservancy has developed a forest conservation program, *Working Woodlands*, which uses revenue from certified forest products and carbon markets to catalyze private forest protection in this region and throughout Pennsylvania.

Wetlands Conservation: Headwaters

The Neversink-Mongaup sub-basin includes significant wetlands. The **Bashakill wetland** is a 3,000-acre emergent marsh formed as a result of large floods that repeatedly deposited natural dams in the early part of the 19th century. Today the water level is maintained by a very small dam that was installed by NY DEC after farmers drained the wetland. The historically deep and meandering Basher Kill flows through the marsh, eventually draining into the Neversink River. Over 200 species of birds have been documented here, and it is home to the only occurrence of the iron color shiner, *Notropis chalybaeus* in New York. The Bashakill also supports a diverse amphibian population, and wild rice, *Zizania aquatica,* occurs here as well. Although the wetland itself is protected as a wildlife management area, priority headwaters surrounding the wetland also are important.

Groundwater/Baseflow Conservation: Headwaters and Wetlands

Baseflow conservation is also an important conservation strategy within the Upper Delaware region. The watersheds of the Lackawaxen River exhibit high baseflow and low groundwater use. The Neversink watershed also overlaps with the Port Jervis trough, which is recognized regionally as an important groundwater area. Several of the larger tributaries in the Upper Delaware watershed provide colder water to the mainstem, which is especially important during summer (PFBC 2007). Maintaining groundwater recharge, forest and wetland conservation, and managing water use is necessary to maintain base flow and provide thermal refugia.

Streamflow Management: Major Tributaries and Upper Mainstem

Since the New York City water supply reservoirs were completed, the four basin states and New York City have worked together to manage reservoir releases for multiple objectives. Interim implementation of the most recent program, the *Flexible Flow Management Program* (FFMP), began in 2007. FFMP is "a framework for managing diversions and releases for multiple objectives, including water supply, drought mitigation, flood mitigation, protection of the tailwaters fishery, a diverse array of habitat needs in the main stem, estuary and bay, recreation and salinity repulsion" (DRBC 2007). Since interim implementation began, experimental adjustments have been made each year in an effort to balance human and ecosystem needs and adjust to changes in river conditions.

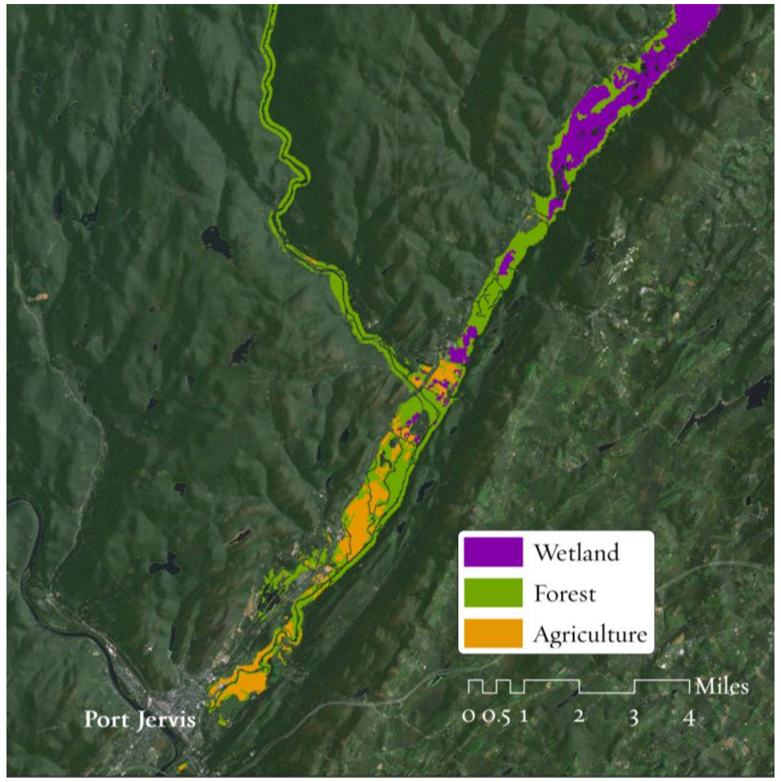


Figure 5.5. Neversink River floodplain complex

Forest and Agricultural Land Conservation: Floodplains

The significant floodplain complex on the **Neversink River** (Figure 5.4) connects to a floodplain complex on its largest tributary, the **Basher Kill**. This complex has been identified as a conservation priority. The lower portion of the complex occurs on an ancient alluvial floodplain above the large Port Jervis aquifer. The water table is very high in the floodplain and provides excellent opportunities for floodplain and riverine wetland restoration opportunities. A large protected floodplain forest community occurs within this complex, which also includes successional grassland and shrub communities, beaver ponds, emergent wetlands, a red maple swamp, and active and fallow agricultural lands. Conservation opportunities include reconnecting the floodplain and expanding the existing floodplain forest community. Some high priority parcels are still in private ownership and should be the focus of protection efforts.

Figure 5.2. Land use in the Upper Delaware River

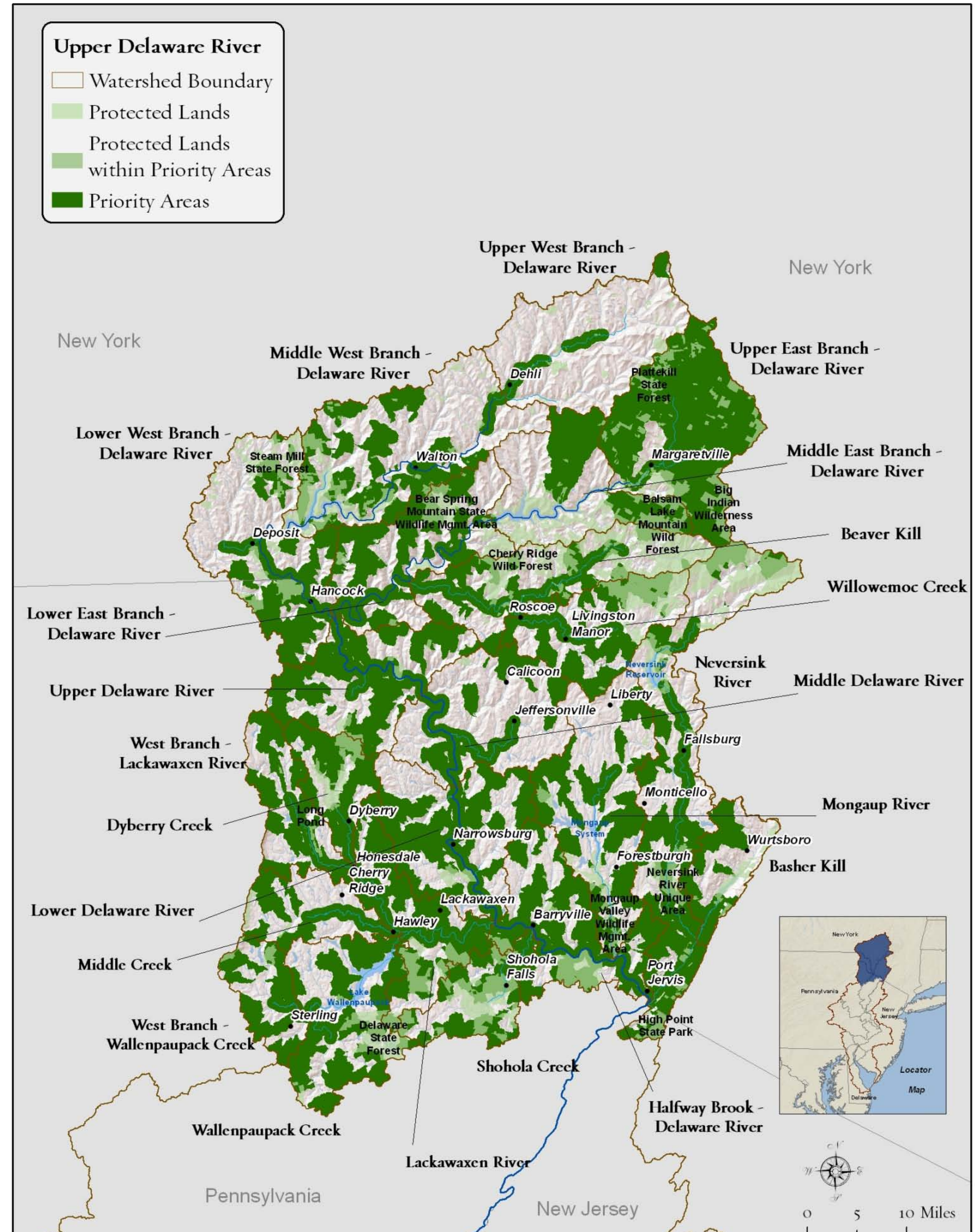


Figure 5.3. Protected lands in the Upper Delaware River

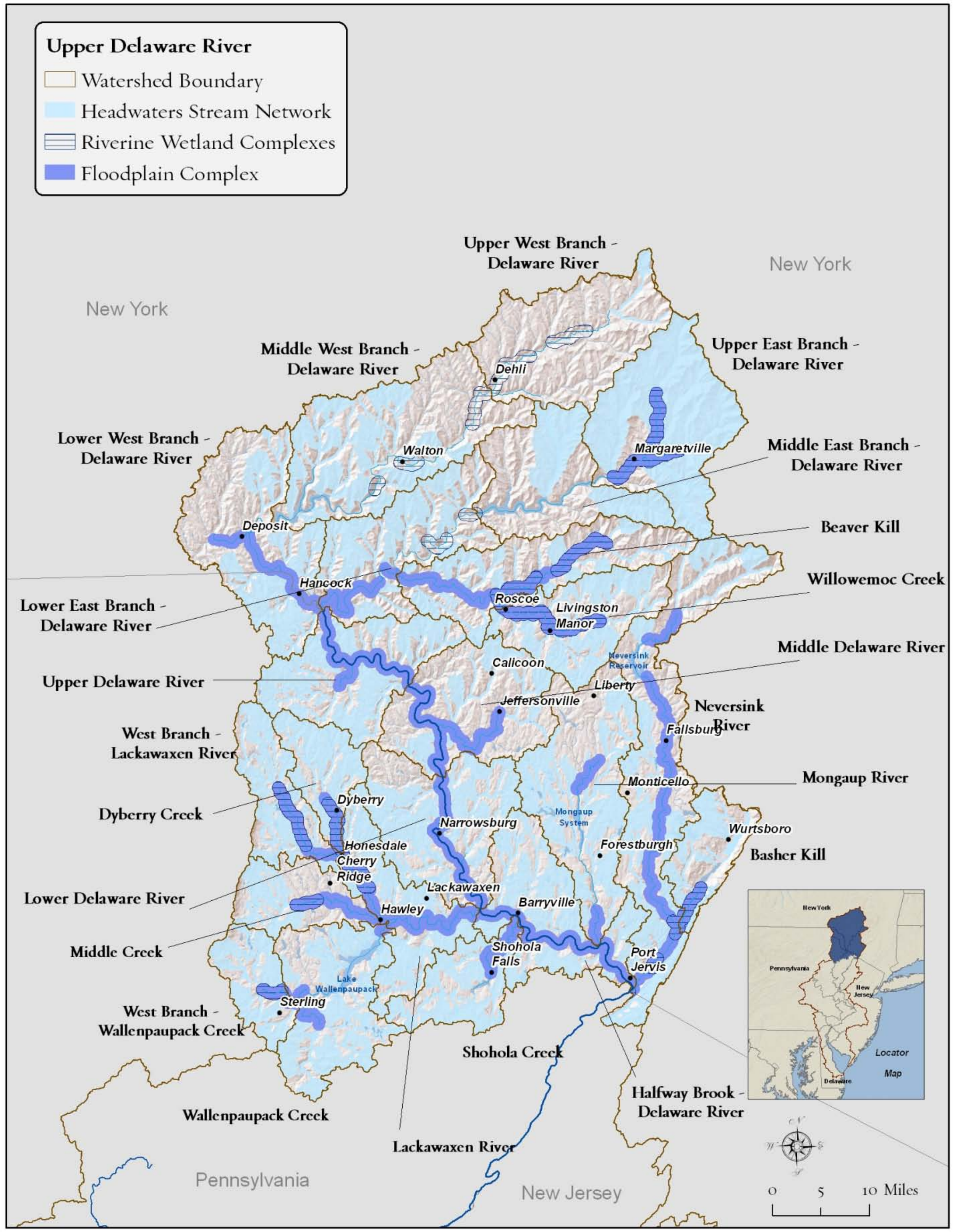


Figure 5.4. Priority conservation areas in the Upper Delaware River by ecosystem type

Table 5.1. Freshwater priorities in Upper Delaware River by watershed

Watershed Name	Freshwater System Priorities	Priority Strategies					
		Forest Conservation	Wetland Conservation	Agricultural Land Protection and Conservation	Aquatic Connectivity Restoration	Streamflow Management	Groundwater/ Baseflow Conservation
		F	W	A	C	D	G
Upper West Branch	Headwater Wetlands; Riverine Wetlands	●		●			
Middle West Branch	Headwater Networks; Riverine Wetlands; Headwater Wetlands;	●		●			
Lower West Branch	Floodplain Complexes; Headwater Networks; Headwater Wetlands	●		●		●	
Upper East Branch	Headwater Networks; Riverine Wetlands; Headwater Wetlands	●	●	●	●		
Middle East Branch	Headwater Networks	●		●		●	
Lower East Branch	Floodplain Complexes; Headwater Networks	●		●		●	
Beaver Kill	Floodplain Complexes; Headwater Networks; Riverine Wetlands; Headwater Wetlands	●	●				
Willowemoc Creek	Floodplain Complexes; Headwater Networks; Riverine Wetlands; Headwater Wetlands	●	●				●
Upper Delaware River	Floodplain Complexes; Headwater Networks; Headwater Wetlands	●	●	●		●	●
Middle Delaware River	Floodplain Complexes; Headwater Networks; Headwater Wetlands	●		●		●	
Neversink River	Floodplain Complexes; Headwater Networks; Riverine Wetlands; Headwater Wetlands	●	●	●	●	●	
Mongaup River	Floodplain Complexes; Headwater Networks; Headwater Wetlands	●	●	●	●	●	
Basher Kill	Floodplain Complexes; Headwater Networks; Riverine Wetlands; Headwater Wetlands	●	●				●
West Branch – Lackawaxen River	Floodplain Complexes; Riverine Wetlands; Headwater Wetlands	●	●		●	●	●
Dyberry Creek	Floodplain Complexes; Headwater Networks; Riverine Wetlands; Headwater Wetlands	●	●		●		●
Lower Delaware River	Floodplain Complexes; Headwater Networks; Headwater Wetlands	●	●	●		●	
Middle Creek	Floodplain Complexes; Headwater Networks; Riverine Wetlands; Headwater Wetlands	●	●		●		●
West Branch – Wallenpaupack Creek	Floodplain Complexes; Headwater Networks; Riverine Wetlands; Headwater Wetlands	●	●			●	●
Wallenpaupack Creek	Floodplain Complexes; Headwater Networks; Headwater Wetlands	●	●			●	●
Lackawaxen River	Floodplain Complexes; Headwater Networks; Riverine Wetlands; Headwater Wetlands	●	●			●	●
Shohola Creek	Floodplain Complexes; Headwater Networks; Headwater Wetlands	●	●			●	●
Halfway Brook	Floodplain Complexes; Headwater Networks; Riverine Wetlands; Headwater Wetlands	●	●			●	●

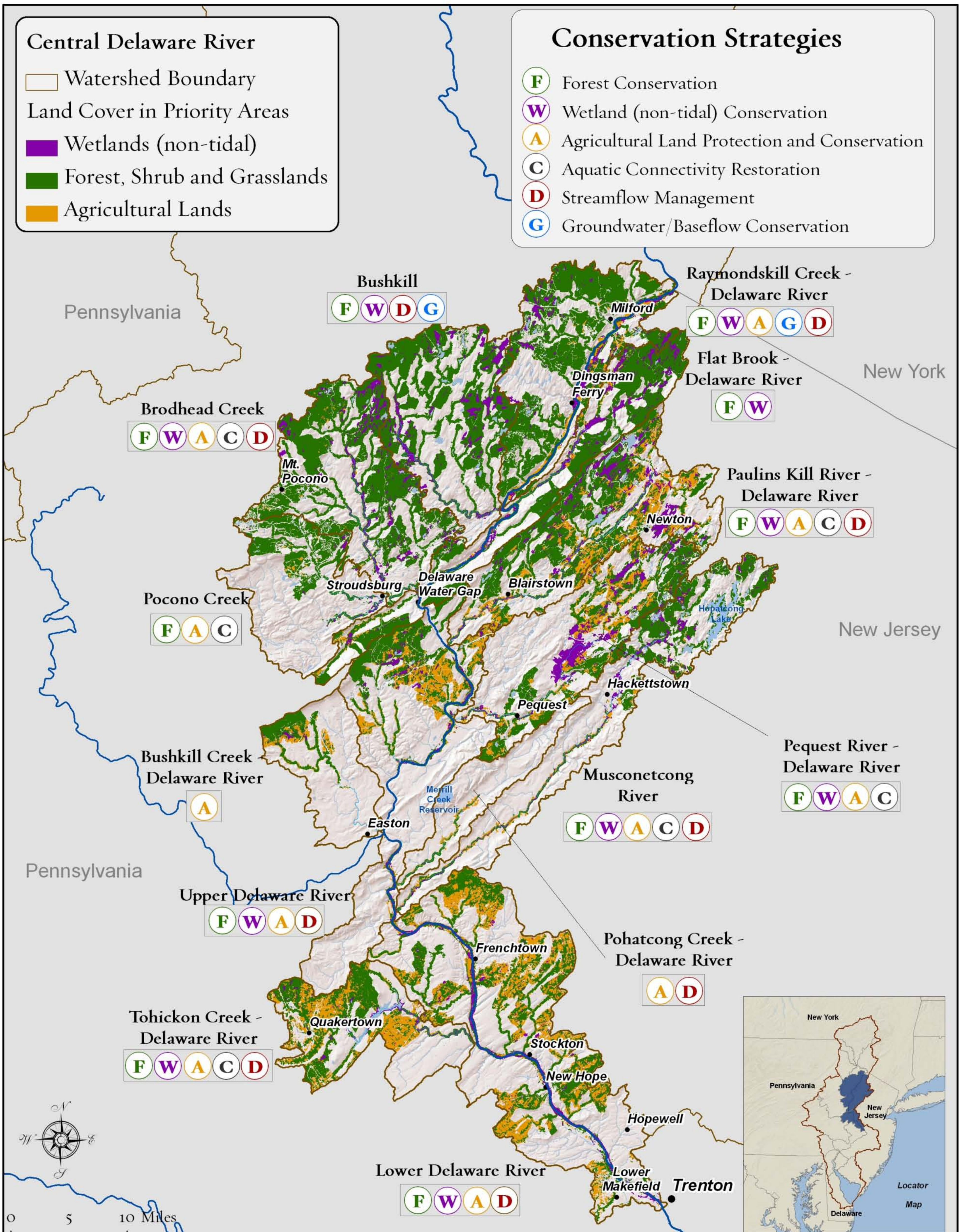


Figure 5.6. Priority conservation areas and recommended conservation strategies in the Central Delaware River

The Central Delaware River

The Central Delaware River ~

The central Delaware River, including the Upper and Lower Sub-basins, extends 121 miles from Matamoras, PA and Port Jervis, NY downstream to the fall line near Trenton, NJ (DRBC 2008). Turning abruptly to the south, the river flows between the ridgelines of the Appalachian Plateau and the Ridge and Valley and is underlain by extensive glacial deposits (Carswell et al 1979, Fletcher et al, 1970, Reynolds 2007, Witte 2001). At the Delaware Water Gap, the river slices through the Ridge and Valley before encountering a series of limestone rapids, notably Foul Rift. Crossing into the Piedmont, the river broadens and becomes increasingly shallow until reaching Trenton Falls, the geologic "Fall Line", created by a narrow wedge of resistant metamorphic rock exposed in the channel. The fall line marks the transition from the tidal to non-tidal Delaware River (DRBC 1991).

Over its course, the river drops approximately 413 feet, crossing the Kittatinny Ridge at the Delaware Water Gap. Tributaries in the region include the Bush kill and Brodhead Creeks in PA and the Flat Brook, Paulins Kill and Musconetcong Rivers in NJ. While forest cover dominates the portions of the basin upstream of the Delaware Water Gap, forests give way to agriculture and urbanization moving downstream (Figure 5.7). In these areas, water quality concerns are most often related to urban, industrial, and agricultural activities (United States Geologic Survey, 1999).

This region was first inhabited by the Lenape Indians who fished and foraged along the banks of the river. By the early 1700s, the Walking Purchase of 1737, smallpox, measles, and escalating conflicts over land and trade forced the Lenape inland away from the Delaware Valley. This opened the way for Europeans to clear the forests for agriculture, build mills to process grain and to manufacture textiles and paper. The Delaware Canal met the need for a better transportation system, running for 60 miles, parallel to the river, from Easton to Bristol, from 1832 to 1931. Today the canal and 830 surrounding acres are designated as the Delaware Canal State Park.

Protected areas are prevalent in this sub-basin (Figure 5.8). While numerous dams have been constructed on tributaries, the mainstem Delaware River remains the longest free-flowing mainstem river east of the Mississippi and is part of the National Wild and Scenic System, which includes two parks: the Delaware Water Gap National Recreation Area and the Lower Delaware Wild and Scenic River. Two major tributaries to the Delaware also have received special protection status; sections of the Musconetcong River in New Jersey also are designated as Wild and Scenic, and in Pennsylvania, the Cherry Valley National Wildlife Refuge, established in 2009, exists along Cherry Creek.

While water quality in many parts of the Basin has improved during the past 25 years due to higher water quality standards, required permits for discharges, and improved enforcement of pollution control programs, impacts still exist in this region. Fish consumption advisories are in place for the entire mainstem due to mercury and polychlorinated biphenols (PCBs). Aquatic life standards are not being met for the mainstem downstream of Easton. Dissolved oxygen and nutrients also are of concern due to point and non-point pollution sources (DRBC 2008).

Bog Turtle © TNC Staff

Bog Turtle ~ The bog turtle (*Glyptemys muhlenbergii*) is one of the world's smallest turtles, growing to only 3-4 inches. In addition to its size, it is readily distinguished by orange blotches on both sides of its neck. As its name suggests, the species inhabits wetlands, specifically, wet meadows and bogs dominated by tussock sedges and grasses. It requires deep mucky soils fed by groundwater seeps and springs (Pennsylvania Natural Heritage Program year, 2010b). Due to the species' specialized habitat requirements and wetland losses, the species is currently listed as endangered in PA, NJ, and DE, and is federally threatened. Bog turtle habitats are scattered throughout the basin with the **Cherry Valley** National Wildlife Refuge being noteworthy among them. Other important strongholds occur in the **Ridge and Valley** and in the **limestone areas of the Piedmont Provinces**. **Wetland Conservation** and **Agricultural Land Protection and Conservation** are critical strategies for the preservation of this and other species.

Conservation Highlights ~

The map on the reverse (Figure 5.6) highlights sub-watersheds within the Upper and Lower Central sub-basin where Forest Conservation, Wetland Conservation, Agricultural Land Protection and Conservation, Aquatic Connectivity Restoration, Streamflow Management, and Groundwater/Baseflow Conservation strategies would help protect and restore basin biodiversity. In addition, Figure 5.9 illustrates the identified priority conservation areas within the sub-basin by ecosystem type, without associated land cover. Specific conservation strategy examples include:

Forest Conservation: Headwaters

In the headwaters of the Upper sub-basin, forest conservation is a priority conservation strategy. Several large unfragmented forested areas provide cores for expanding headwater conservation, especially in the **Brodhead, Bushkill, Raymondskill,** and **Flat Brook** watersheds. Several funds and programs are available to help landowners protect forested headwaters in this region. For example, the *Common Waters Fund* provides funding to support the development of forest stewardship plans, to implement forest management practices, and for conservation easements. In addition, The Nature Conservancy has developed a forest conservation program, *Working Woodlands*, which uses revenue from certified forest products and carbon markets to catalyze private forest protection in this region and throughout Pennsylvania.

Wetland Conservation: Headwaters

Wetland conservation is also a high priority conservation strategy, particularly in the Upper Central sub-basin. The greatest diversity of wetlands in the state of Pennsylvania is within the glaciated portions of the Allegheny Plateau, where many Delaware Basin headwater streams originate (Davis 1993). Boreal conifer swamps, oligotrophic kettlehole bogs, cranberry and bog-rosemary peatlands, and acidic broadleaf swamps occur throughout the region. **Long Pond** (**Pocono Creek** watershed) and **Mashipacong Bogs** (**Flat Brook** watershed) reveal the region's boreal heritage, harboring species tolerant of cooler temperatures. Other unique wetland communities are found along the Limestone Valley, where rich groundwater provides the minerals to support calcareous fens, seepage swamps, and limestone wetlands. Cherry Valley National Wildlife Refuge and the Mt. Bethel Fens in PA and the Johnsonburg and Sussex Swamps in NJ contain examples of these systems. Vernal pools are also scattered throughout the region, with concentrations along the toeslopes of the Kittatinny Ridge.

Forest and Agricultural Land Conservation: Floodplains

Three major floodplain complexes along the mainstem Delaware River also are identified as conservation priorities (Figure 5.10): the **Delaware Water Gap Floodplain Complex**; the **Middle Delaware Floodplain Complex** (from the Paulins Kill to Martins Creek); and the **Lower Delaware Floodplain Complex** (from Lehigh to Trenton). The Delaware Water Gap floodplain complex extends approximately 31 miles, includes 3,700 acres (58% is in natural cover), and much of it is within protected lands. It is a relatively large mosaic of interconnected floodplain communities, including high and low terrace floodplain forests, shrublands, grasslands, wetlands, and other herbaceous communities. This floodplain complex also links to tributary floodplain complexes along the **Bushkill Creek** and **Flat Brook**. Conservation opportunities include reconnecting the floodplain, some of which is in agriculture, to the river. This management strategy allows for inundating the floodplain to provide ecological benefits and potentially to reduce flood damage locally and downstream (American Rivers 2010). Recently-completed flood inundation mapping by the National Weather Service exists for several areas along the mainstem. These maps show the spatial extent of expected flooding and, in addition to helping to predict which roadways, streets, buildings, airports, agricultural fields, etc., are likely to be impacted by floodwaters, they can be used to identify potential natural and open areas that could be inundated to restore some floodplain functions.

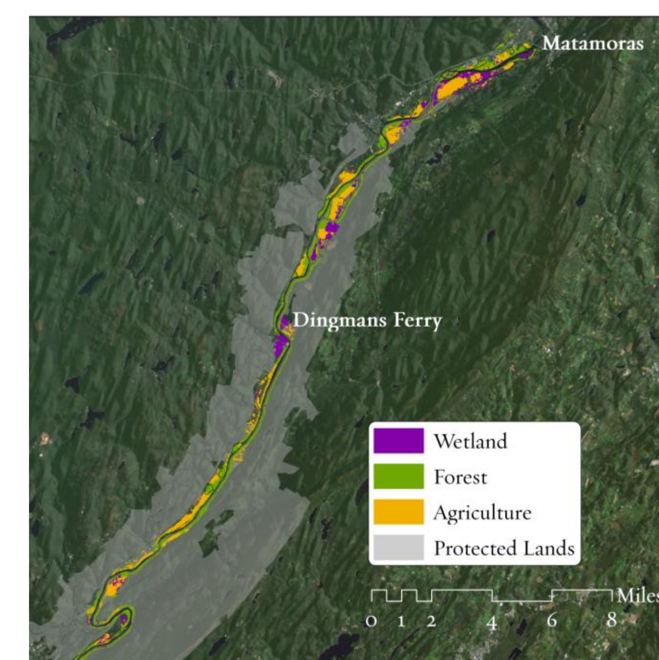


Figure 5.10. Delaware Water Gap floodplain complex

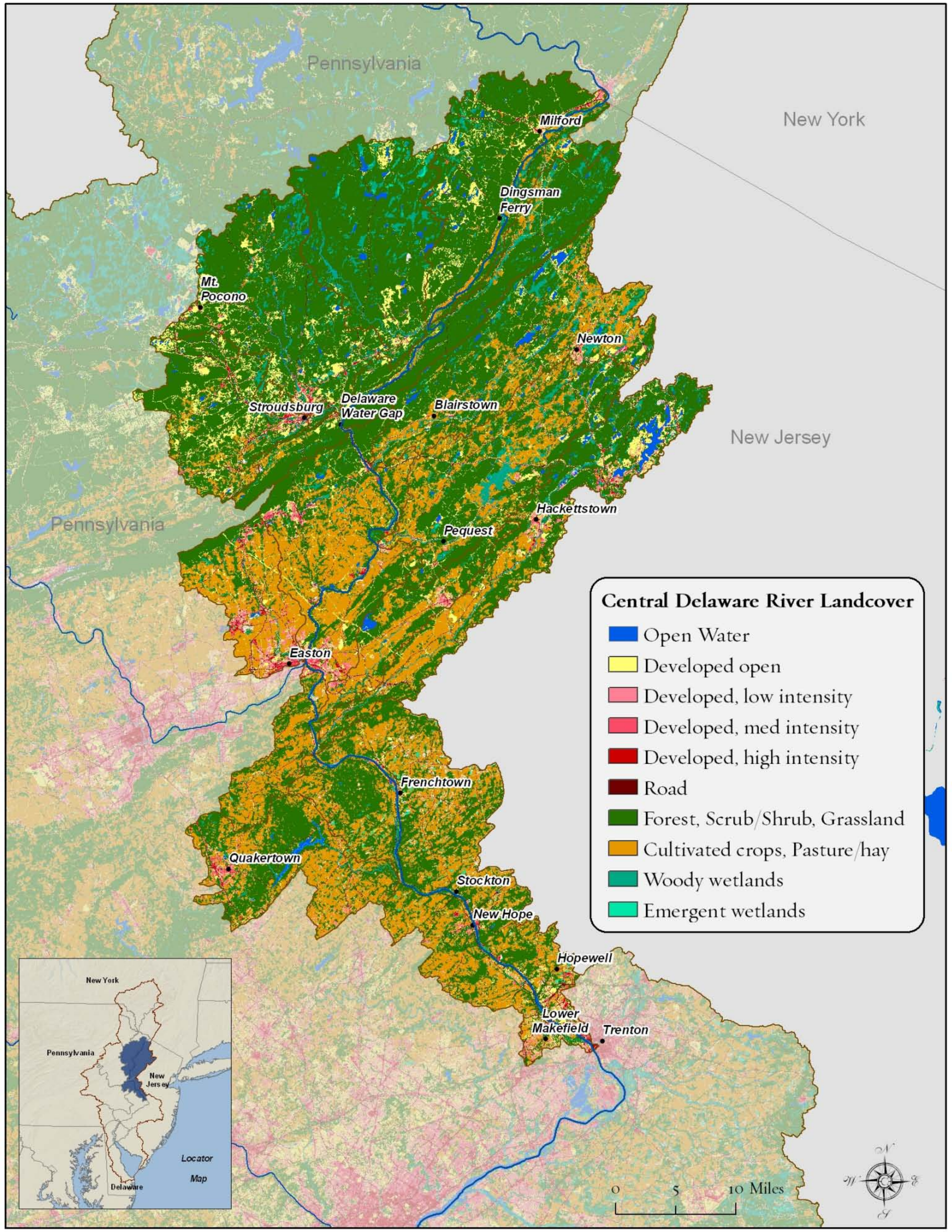


Figure 5.7. Land use in the Central Delaware River

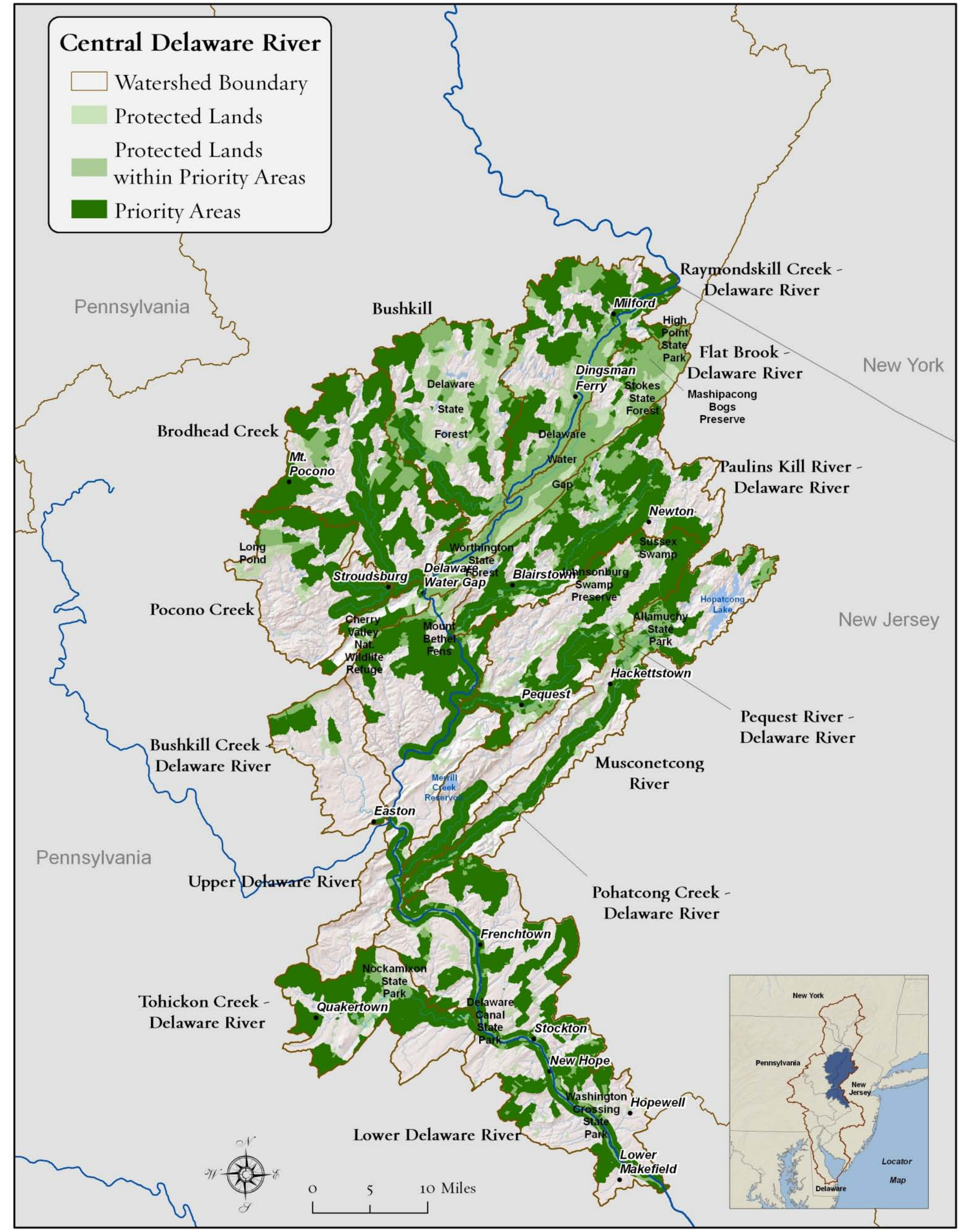


Figure 5.8. Protected lands in the Central Delaware River

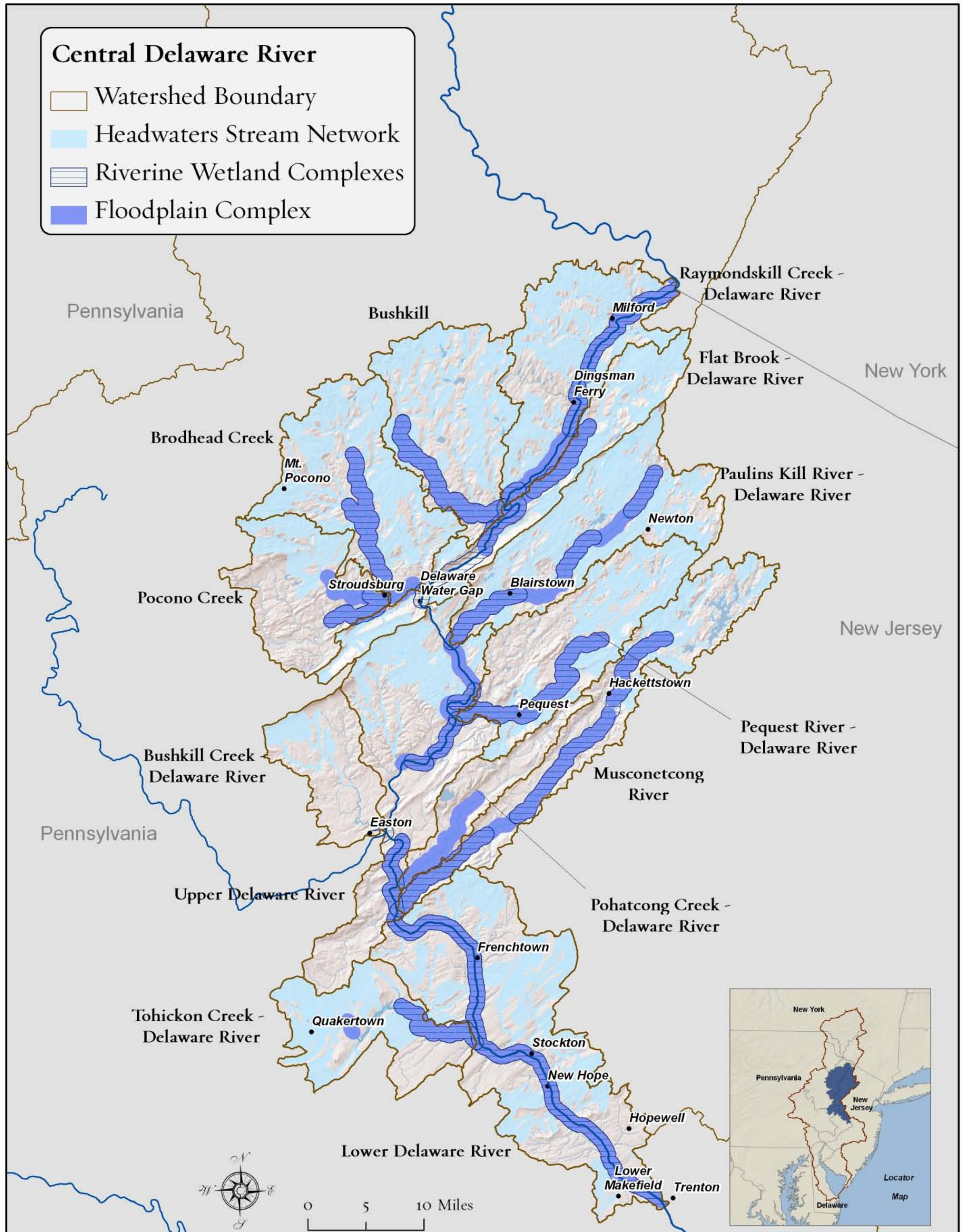


Figure 5.9. Priority conservation areas in the Central Delaware River by ecosystem type

Watershed	Freshwater System Priorities	Priority Strategies					
		Forest Conservation	Wetland Conservation	Agricultural Land Protection and Conservation	Aquatic Connectivity Restoration	Streamflow Management	Groundwater/ Baseflow Conservation
		F	W	A	C	D	G
Bushkill	Floodplain Complexes; Headwater Networks; Headwater Wetlands; Riverine Wetlands	●	●			●	●
Raymondskill Creek - Delaware River	Floodplain Complexes; Headwater Networks; Headwater Wetlands; Riverine Wetlands	●	●	●		●	●
Flat Brook - Delaware River	Floodplain Complexes; Headwater Networks; Headwater Wetlands; Riverine Wetlands	●	●				
Paulins Kill River - Delaware River	Floodplain Complexes; Headwater Networks; Headwater Wetlands; Riverine Wetlands	●	●	●	●	●	
Brodhead Creek	Floodplain Complexes; Headwater Networks; Headwater Wetlands; Riverine Wetlands	●	●	●	●	●	
Pocono Creek	Floodplain Complexes; Headwater Wetlands; Riverine Wetlands	●		●	●		
Pequest River - Delaware River	Floodplain Complexes; Headwater Networks; Headwater Wetlands; Riverine Wetlands	●	●	●	●		
Bushkill Creek - Delaware River	Headwater Wetlands			●			
Musconetcong River	Floodplain Complexes; Headwater Networks; Headwater Wetlands; Riverine Wetlands	●	●	●	●	●	
Upper Delaware River	Floodplain Complexes; Headwater Wetlands; Riverine Wetlands	●	●	●			
Tohickon Creek - Delaware River	Floodplain Complexes; Headwater Networks; Headwater Wetlands;	●	●	●	●	●	
Lower Delaware River	Floodplain Complexes; Headwater Networks; Headwater Wetlands; Riverine Wetlands	●	●	●		●	

Table 5.2. Freshwater priorities in Central Delaware River by watershed

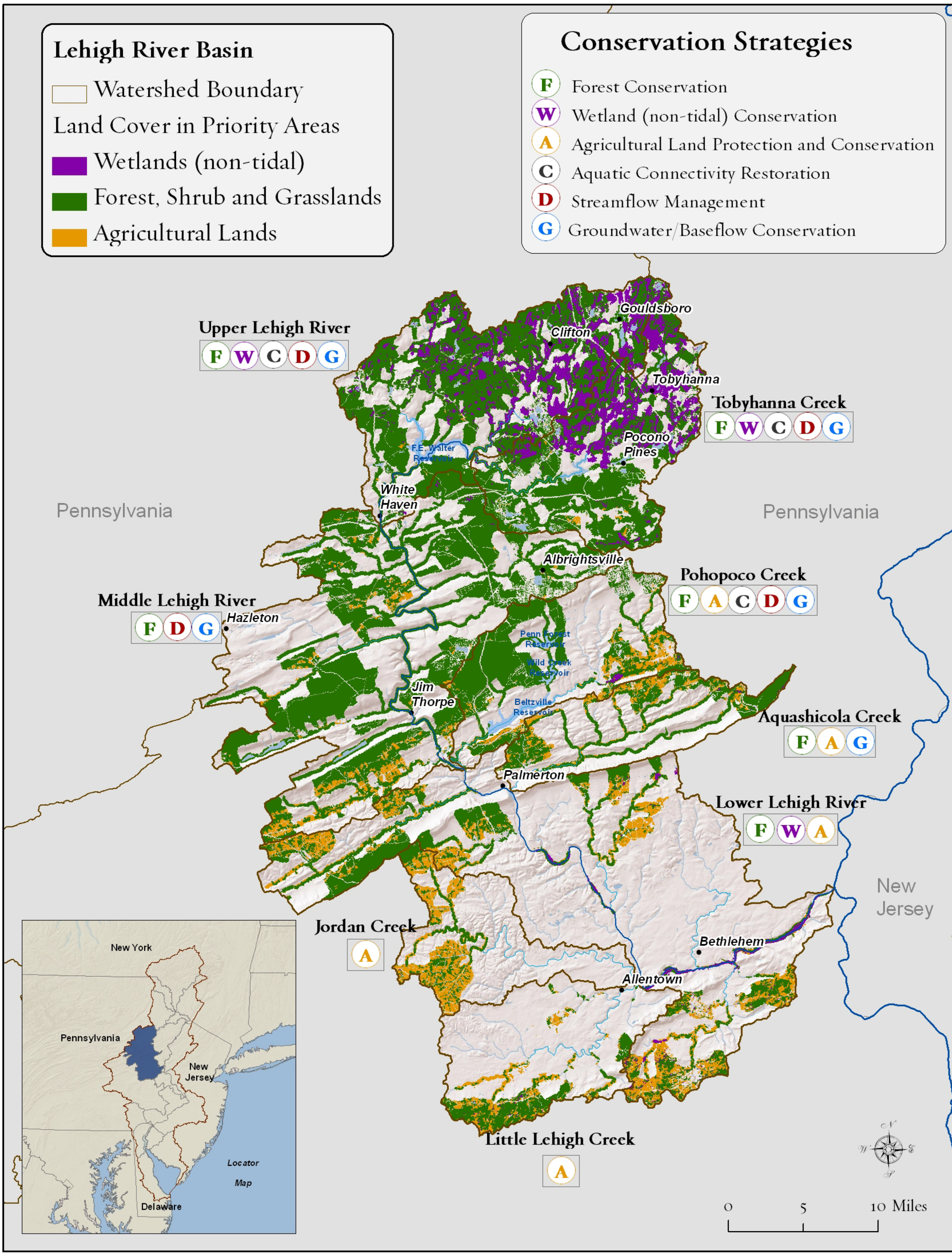


Figure 5.11. Priority conservation areas and recommended conservation strategies in the Lehigh River basin.

The Lehigh River Basin

The Lehigh River Basin ~

Located in northeastern Pennsylvania, the Lehigh River is the second largest tributary to the Delaware River, draining approximately 1,345 square miles. It drops nearly 2,000 feet in elevation, arising from glacial bogs in its headwaters, then flowing across Blue Mountain at Lehigh Gap to its confluence with the mainstem Delaware at the town of Easton, PA (Figure 5.12). The unique character and natural resources of each physiographic region, including the Appalachian Plateau, Ridge and Valley, New England, and Piedmont Provinces, significantly shaped the history and land use of the Lehigh watershed.

From the late 1700s until the early 1900s, major industries, economies and towns were developed in the area, altering the landscape and water quality of the Lehigh watershed. In 1829, The Lehigh Coal and Navigation Company opened a 72-mile long series of locks and dams to transport raw materials downstream to manufacturing centers. Cities such as Bethlehem and Coplay used these raw materials and water from the river to produce steel and cement. In 1873, the Lehigh Valley region was the number one producer of iron-ore in Pennsylvania, and until 1907 the region produced more than half of all the Portland cement used in the United States.

Starting in the 1820s, the mainstem Lehigh River also became fragmented by the construction of four dams. Three dams, the Easton, Chain, and Hamilton Street Dams, supplied water to the canal system, while the fourth, Northampton Dam, was constructed to supply water to Whitehall Cement Company. Local and regional railroads replaced the canal system; however, the mainstem dams remained. Fish passage structures are currently in place for three of the four lower mainstem dams, although they are not sufficiently effective to restore American shad to the Lehigh River (PFBC 2007).

The Industrial Revolution left its mark on the watershed and on the waters of the Lehigh River. However, per the Lehigh River Watershed Conservation Plan, the Lehigh River is cleaner now than anytime during the past 150 years (Wildlands Conservancy 2007).

The upper portion of the Lehigh exhibits only minor water quality issues, specifically low dissolved oxygen levels and high temperatures due to the abundance of small ponds and wetlands in the region. In the middle portion of the basin, acid mine drainage (AMD) from four tributaries – Sandy Run, Buck Mountain, Black Creek, and Nesquehoning Creek – results in elevated metal concentrations and low pH. In the lower portion of the basin, areas of carbonate geology help to buffer the impacts of upstream AMD; however, agriculture and development have caused other water quality issues. Thermal impacts, sedimentation, excess nutrient loading, and polluted stormwater contributions are seen in the lower Lehigh and its tributaries. In addition, twelve superfund sites occur throughout the Lehigh basin.

Over 100 years later, approximately 59% of the watershed is in natural cover with 55% being forests and 4% being wetlands. The remainder is primarily a mixture of agriculture (21%) and urban (17%) lands. Preserved lands occur throughout the watershed, but are concentrated north of Blue Mountain (Figure 5.13). Lands preserved by federal, state, and non-profit organizations account for over 180,000 acres, or approximately one third of the forested land cover in the watershed.

Louisiana Waterthrush ~ Headwater Conservation

The Louisiana waterthrush (*Seiurus motacilla*) is a forest interior songbird that breeds in the headwater regions of the Delaware River Basin. Its reliance on high-quality aquatic and terrestrial systems makes the species a potential indicator of ecological integrity of headwater stream systems (O'Connell et al. 2003; Mattsson and Cooper 2006).

The waterthrush is most frequently found along medium- to high-gradient, 1st to 3rd orderheadwater streams of mature, forested watersheds. In northeastern Pennsylvania, specifically the Pocono Region, they show an affinity for shady eastern hemlock-dominated ravines and are found primarily along the Pocono Plateau perimeter, where such streams are prominent (Ross et al. 2004; Master pers. comm. 2007)

Because they depend on aquatic macroinvertebrates for food, the Louisiana waterthrush is sensitive to water quality degradation. By conserving high-quality **headwater systems** and **riparian corridors**, we also preserve these areas for a diversity of other wildlife and maintain the functional services these systems provide.

Louisiana waterthrush - ©Lloyd Sputnik

Conservation Highlights ~

The map on the reverse (Figure 5.11) highlights sub-watersheds within the Lehigh River basin where Forest Conservation, Wetland Conservation, Agricultural Land Protection and Conservation, Aquatic Connectivity Restoration, Streamflow Management, and Groundwater/Baseflow Conservation strategies would help protect and restore basin biodiversity. In addition, Figure 5.14 illustrates the identified priority conservation areas within the basin by ecosystem type, without associated land cover. Specific conservation strategy examples include:

F W Forest and Wetland Conservation: Headwaters and Floodplains

Forest and wetland conservation are key conservation strategies, particularly in the upper half of this watershed. Although natural resource extraction was extensive in this region, second growth forests, many of which are already preserved, have reestablished along the floodplains and in the headwaters. The area of the Lehigh Gorge, a 32-mile long stretch of the mainstem Lehigh River between the Francis E. Walter Dam and the town of Jim Thorpe, PA, provides the backbone for future floodplain conservation efforts. The floodplain complex contains approximately 3,224 acres of natural cover, 53% of which is already preserved. Core forests also exist outside the Lehigh Gorge, including the many headwater systems particularly in the **Upper Lehigh River** and **Tobyhanna Creek** watersheds. Forest and wetlands in existing protected areas serve as the building blocks for future headwater catchment and riparian corridor conservation. Expanding upon existing preserved lands, including the Lackawanna State Forest, Gouldsboro and Tobyhanna State Parks, and State Game Lands 91, 127, 135, and 312, as well as those along the Lehigh Gorge and Blue Mountain, is essential to maintaining water quality and quantity for downstream ecosystems and water users (Figure 5.15). The conservation of headwater areas can be achieved using riparian buffers and other tools. Wenger (1999) suggests that riparian buffers include a base width that can be expanded as necessary to include the full extent of the floodplain, including adjacent wetlands and their associated buffers. To provide habitat for forest interior species such as the Louisiana waterthrush, at least some preserved riparian tracts should be 300 to 600 ft wide (PGC and PFBC 2005; Wenger 1999).

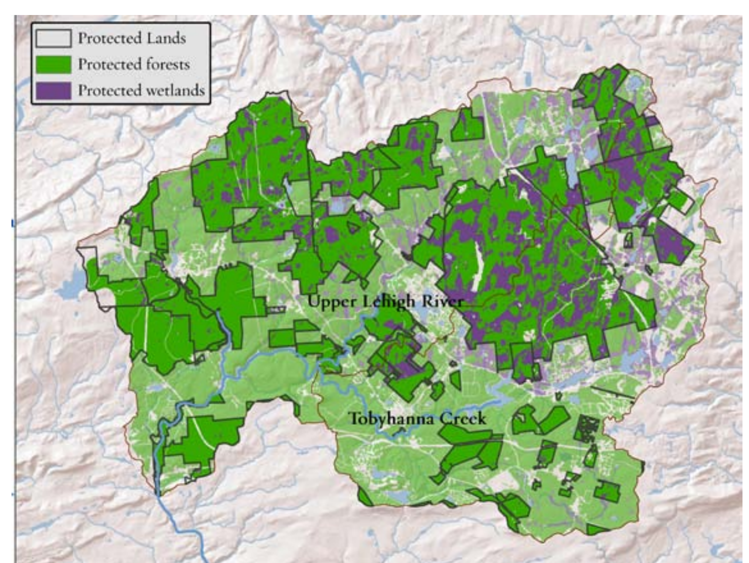


Figure 5.15. Forests and wetlands, Upper Lehigh and Tobyhanna watersheds

C Aquatic Connectivity: Connected Rivers

Five dams occur on the **mainstem Lehigh River**: the Easton, Chain, Hamilton Street, Northampton, and F. E. Walter Dams. From Hamilton Street Dam to F.E. Walter Dam, the Lehigh River is unfragmented for approximately 61 miles. In addition, numerous unfragmented tributaries are connected to this portion of the mainstem, creating a network of over 300 miles of connected stream habitat. Efforts are underway to evaluate the feasibility of full or partial removal of the two lower dams to further improve fish passage to levels that support the return of a healthy American shad population.

G Groundwater/Baseflow Conservation: Headwaters and Wetlands

Baseflow conservation also is an important conservation strategy within the Lehigh watershed. The forested headwaters of the **Upper** and **Middle Lehigh Rivers**, **Tobyhanna**, **Pohopoco** and **Aquashicola Creek** watersheds exhibit high baseflow contributions and low groundwater use. Although some stream systems in this area are impacted by AMD and heavy metal contamination, several of the larger tributaries provide colder water to the mainstem, which is especially important during summer (PFBC 2007). Maintaining the ecological integrity of these watersheds through forest and wetland conservation, while also managing water use, is necessary to maintain baseflow and provide thermal refugia.

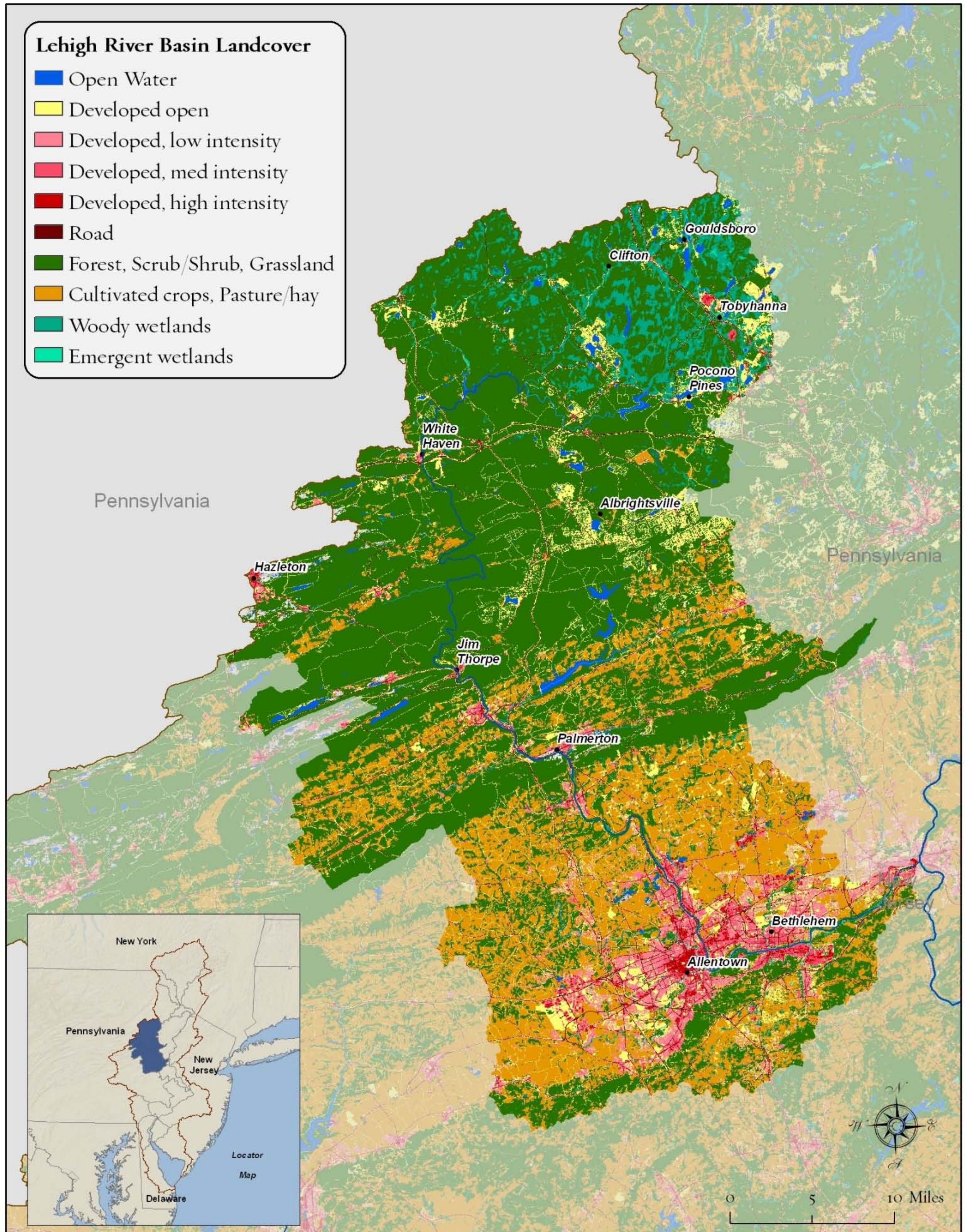


Figure 5.12. Land use in the Lehigh River basin

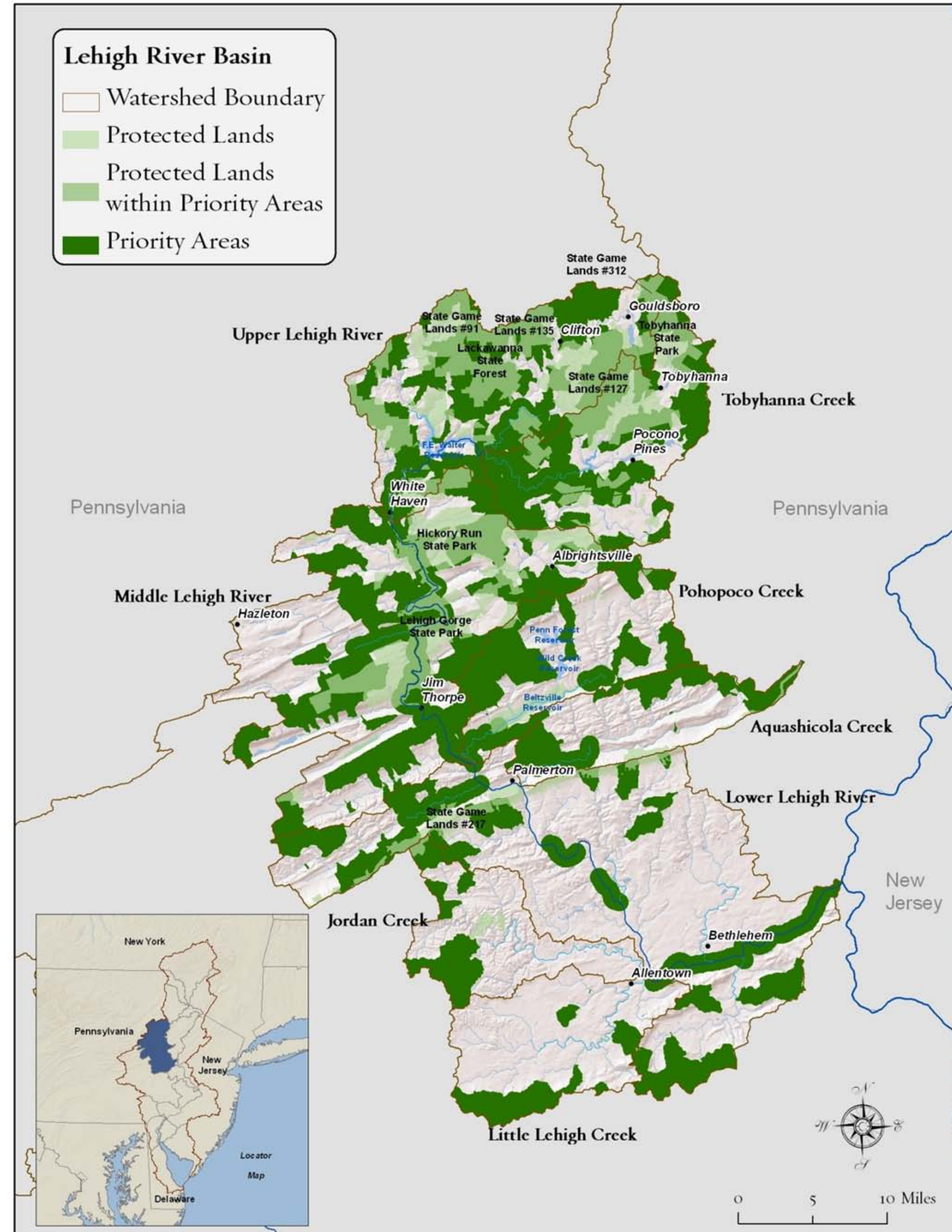


Figure 5.13. Protected lands in the Lehigh River basin

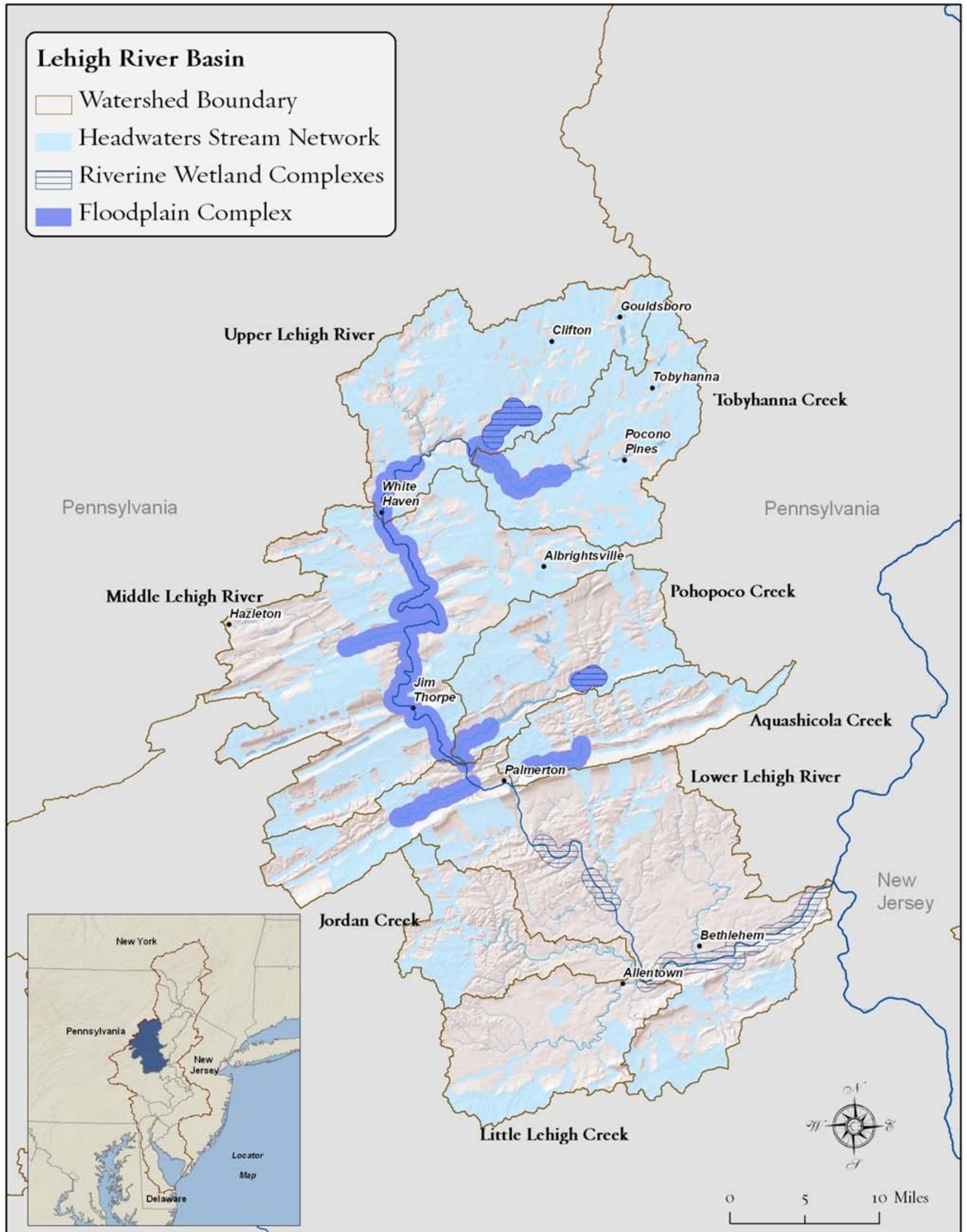


Figure 5.14. Priority conservation areas in the Lehigh River basin by ecosystem type

Watershed	Freshwater System Priorities	Priority Strategies					
		Forest Conservation	Wetland Conservation	Agricultural Land Protection and Conservation	Aquatic Connectivity Restoration	Streamflow Management	Groundwater/ Baseflow Conservation
		F	W	A	C	D	G
Upper Lehigh River	Floodplain Complexes; Headwater Networks; Headwater Wetlands; Riverine Wetlands	●	●		●	●	●
Tobyhanna Creek	Floodplain Complexes; Headwater Networks; Headwater Wetlands;	●	●		●	●	●
Middle Lehigh River	Floodplain Complexes; Headwater Networks;	●				●	●
Pohopoco Creek	Floodplain Complexes; Headwater Networks; Headwater Wetlands; Riverine Wetlands	●		●	●	●	●
Aquashicola Creek	Floodplain Complexes; Headwater Networks	●		●			●
Jordan Creek	Headwater Wetlands			●			
Lower Lehigh River	Floodplain Complexes; Headwater Networks; Headwater Wetlands; Riverine Wetlands	●	●	●			
Little Lehigh Creek	Headwater Wetlands; Riverine Wetlands			●			

Table 5.3. Freshwater priorities in Lehigh River basin by watershed

Schuylkill River Basin:

Priority Conservation Areas and Strategies

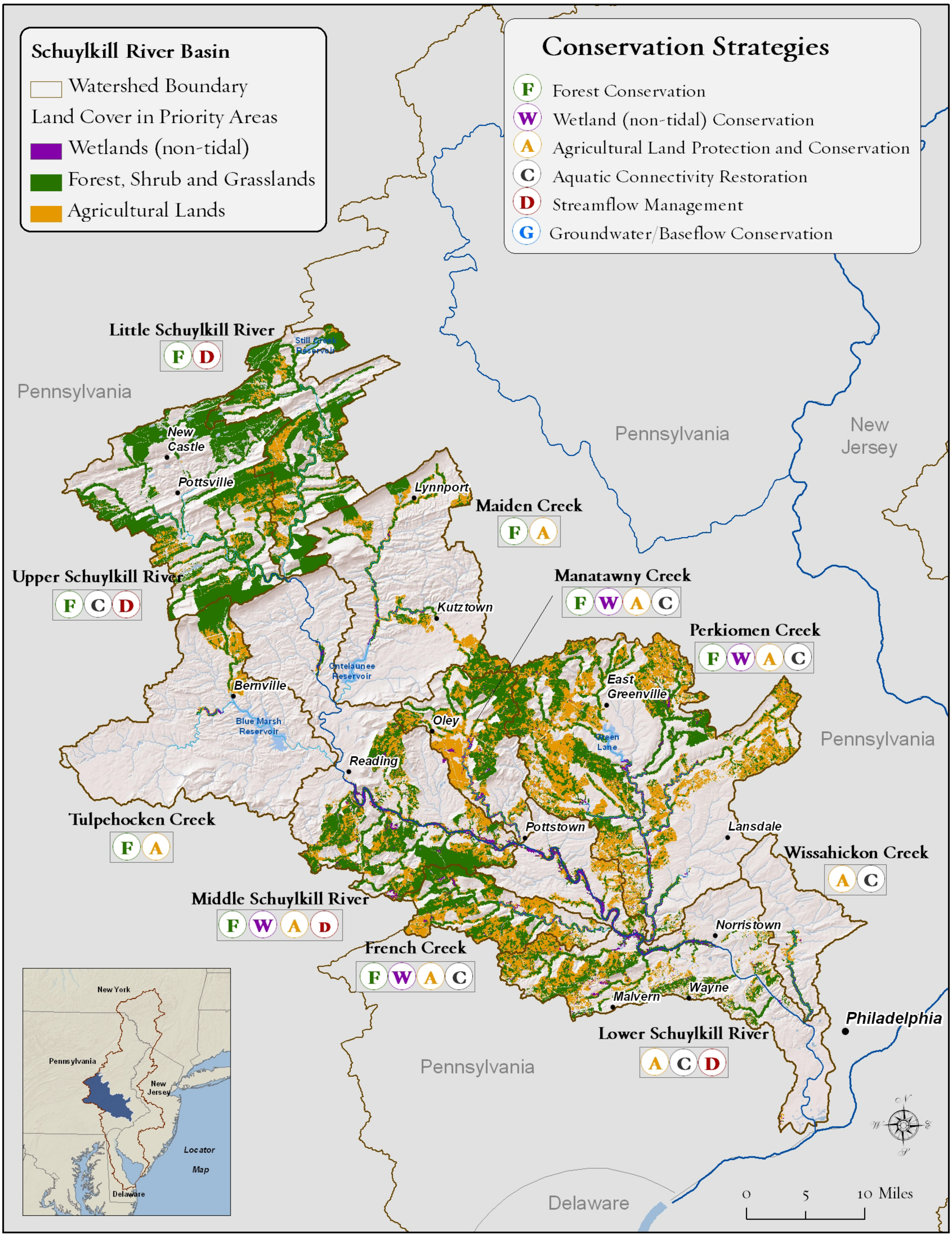


Figure 5.16. Priority conservation areas and recommended conservation strategies in the Schuylkill River basin

The Schuylkill River Basin ~

Located in southeastern Pennsylvania, the Schuylkill watershed, draining almost 2,000 square miles, is the largest major river tributary to the Delaware mainstem, supplying approximately one quarter of the mainstem's flow (Durlin and Schaffstall 1997). Its major cities include Philadelphia, Norristown, Pottstown, and Reading .

The historical legacy of the Schuylkill is as varied as its physiography, which includes the Ridge and Valley, New England, Piedmont, and Coastal Plain Provinces. The Lenape Indians, the Dutch, and the Swedes historically inhabited the watershed, as did William Penn, George Washington, and Benjamin Franklin. Early settlers relied heavily on agriculture for their livelihoods, but vast natural resources of coal, iron ore, and hardwood also fueled thriving industries that depended on the river as a transportation conduit. Each brought temporary economic prosperity and population growth, but each also left behind legacies of habitat destruction, fragmentation, and water pollution. Pollution was so severe that surveys conducted by the city of Philadelphia between 1886 and 1946 recommended that the Schuylkill and Delaware Rivers be abandoned as drinking water sources (Philadelphia Water Department 2010).

In the headwaters of the Schuylkill, acid mine drainage (AMD) and sediment loading are the major water quality problems, impairing miles of headwater streams. In the upper-central and central portions of the basin, agricultural impacts emerge (Figure 5.17). In the lower-central and lower portions of the basin, approximately one-third of the impaired streams are impacted by urban runoff, most of which occur in the highly developed areas of Philadelphia and surrounding suburbs. Along much of the Schuylkill mainstem, fish consumption advisories continue, reflecting the legacy of polychlorinated biphenyls and mercury contamination. Numerous permitted industrial point source and sewage discharges occur throughout the watershed, many of which are located along the mainstem (The Conservation Fund 2003).

Yet today, the Schuylkill River Watershed shows signs of recovery. Approximately 24% of the watershed is designated as high quality or exceptional value waters. More than 16,000 acres of abandoned mine lands have been reclaimed in Schuylkill County alone. Although dominant species such as the towering American chestnut have all but disappeared, forests are returning to the basin. Seven percent of the watershed is in conservation lands, some of the largest of which are French Creek State Park and Hopewell Furnace National Historic Site, Valley Forge National Historic Park, and conserved lands along the Kittatinny Ridge and around the Blue Marsh Reservoir (Figure 5.18).

American Shad ~

The Schuylkill is one of the most storied rivers in the history of American shad (*Alosa sapidissima*) (McPhee 2002). The Delaware River Basin and its tributaries supported some of the largest landings of American shad ever recorded (11-17 million lbs) (Stevenson 1899; Chittenden 1974). In spite of the species' importance and cultural significance, dams and water pollution led to its demise. In 1813, the Shawmont and Reading Dams closed the upper Schuylkill to migrating shad. By 1820, the Fairmont Dam, constructed at the mouth of the Schuylkill, effectively blocked the mainstem for shad passage. For more than 150 years, American shad disappeared from the Schuylkill River. **Aquatic Connectivity Restoration** at appropriate locations along the mainstem Schuylkill and its tributaries could help improve overall shad populations.

Conservation Highlights ~

The map on the reverse (Figure 5.16) highlights sub-watersheds within the Schuylkill River Basin where Forest Conservation, Wetland Conservation, Agricultural Land Protection and Conservation, Aquatic Connectivity Restoration, and Streamflow Management strategies would help protect and restore basin biodiversity. In addition, Figure 5.19 illustrates the identified priority conservation areas within the basin by ecosystem type, without associated land cover. Specific conservation strategy examples include:

(F) Forest Conservation: Headwater and Riparian Corridors

Large unfragmented forests of the **Upper and Little Schuylkill River** watersheds stem from a network of state game lands and state parks clustered around and near the Kittatinny Ridge. Over 40,000 acres of forest reserves, connected by forested riparian corridors of headwater streams, protect water quality, habitat, and the aquatic diversity of these and downstream watersheds. Future headwater riparian corridor conservation can build on these existing preserved areas (Figure 5.18). In the central and lower portions of the Schuylkill, specifically the **Manatawny**, **French**, **and Perkiomen Creek** watersheds, forested areas are generally smaller, more fragmented, and more likely to be privately owned than in the upper portion. Here, forest lands are interspersed among agricultural, residential, and commercial uses. Future riparian conservation can be anchored around large preserved lands, including French Creek State Park and Hopewell National Historic Site, an approximately 7,500 acre forested area within a highly developed portion of southeastern Pennsylvania. Valley Forge National Park and Evansburg State Park also provide core protected lands. Several smaller state game lands exist in this area, but many forested headwaters are in private ownership. Landowner outreach to increase awareness of conservation options – including acquisition, conservation easements, and forest management – could help build contiguous, forested headwater and riparian networks in both public and private ownership.

(F) (W) (A) Forest and Wetland Conservation: Floodplains and Riverine Wetlands

Conservation of floodplains and the wetlands within them is critical to maintain floodplain functions, such as storing floodwaters and sediment, trapping and filtering nutrients, and providing essential wildlife and recreation habitat. In the **Middle and Lower Schuylkill River** watersheds, floodplain forest and riverine wetland conservation are essential conservation strategies, and there is potential to manage agricultural lands in the floodplain to restore some floodplain functions. A nearly continuous floodplain complex occurs between Reading and King of Prussia (approximately 35 miles). However, major highways (such as Rt. 422), railroads, development, and agriculture directly impact this complex. Approximately 50% of this 4,000 acre floodplain complex is in natural cover, including approximately 630 acres of riverine wetlands. In this complex, protection needs to be coupled with restoration and management to enhance the floodplains' functional value. For example, in areas of the floodplain where agricultural use has been retired, floodplain restoration is a conservation option; however, in areas of active agriculture, best management practices aimed to reduce runoff and increase flood storage capacity are potential conservation strategies. The Schuylkill River Trail, proposed to extend from Pottsville to Philadelphia, provides an opportunity to engage the public, various regional, county, and municipal planning agencies, and non-profits in a cooperative effort to preserve and restore this riverine system.

(C) Aquatic Connectivity Restoration: Schuylkill Mainstem and Tributaries

Along the mainstem, ten major dams once blocked fish access. In the 1980s, PFBC began efforts to bring shad back to the Schuylkill. Now, four of these dams have fishways in place: Fairmont, Flat Rock, Norristown, and Black Rock Dams. Three dams – Plymouth, Vincent, and Felix Dams – are now breached or are planned to be breached. These efforts have re-opened the lower and middle Schuylkill River to migrating shad (PFBC 2011).

Dams are also widespread on the Schuylkill's tributaries. Over 200 dams, many of them low-head dams, still exist in the watershed. Yet some large connected stream networks, ranging from 25 to 100 stream miles in length, exist in the **Upper Schuylkill River**, **Tulpehocken**, **Manatawny**, **French Creek**, and **Perkiomen Creek** watersheds. Several of these connected stream networks are disconnected from the mainstem Schuylkill by major reservoirs, including the Blue Marsh Reservoir (Tulpehocken watershed) and the Green Lane Reservoir (Perkiomen watershed) (Figure 5.20). These reservoirs not only fragment the river, but also can impact the river's natural flow regime.

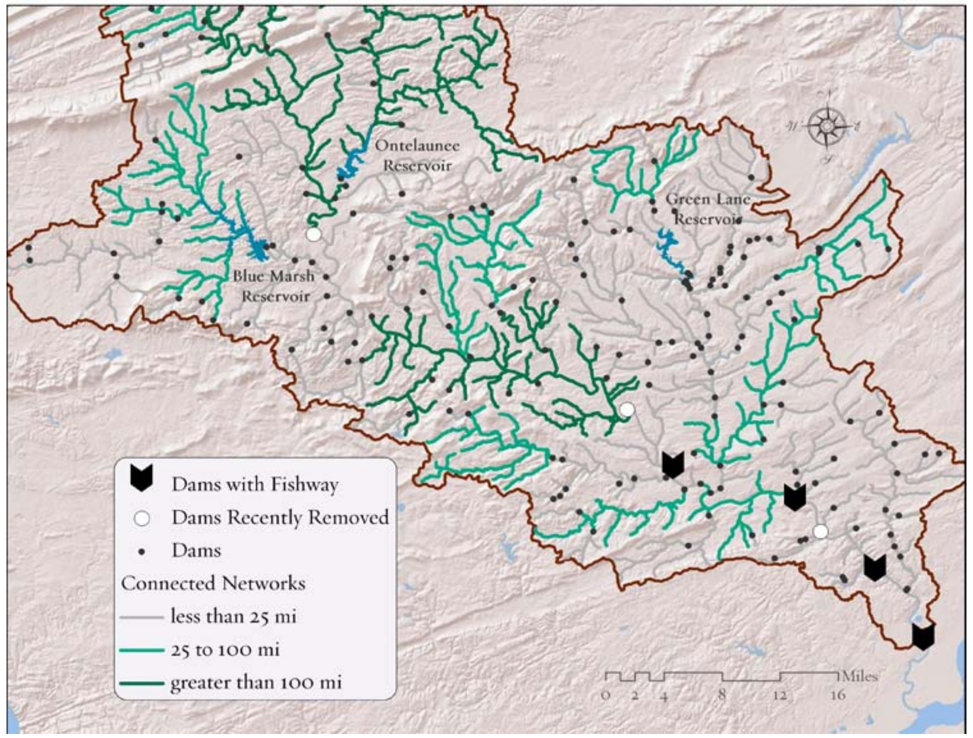


Figure 5.20. Reservoirs in Schuylkill tributaries

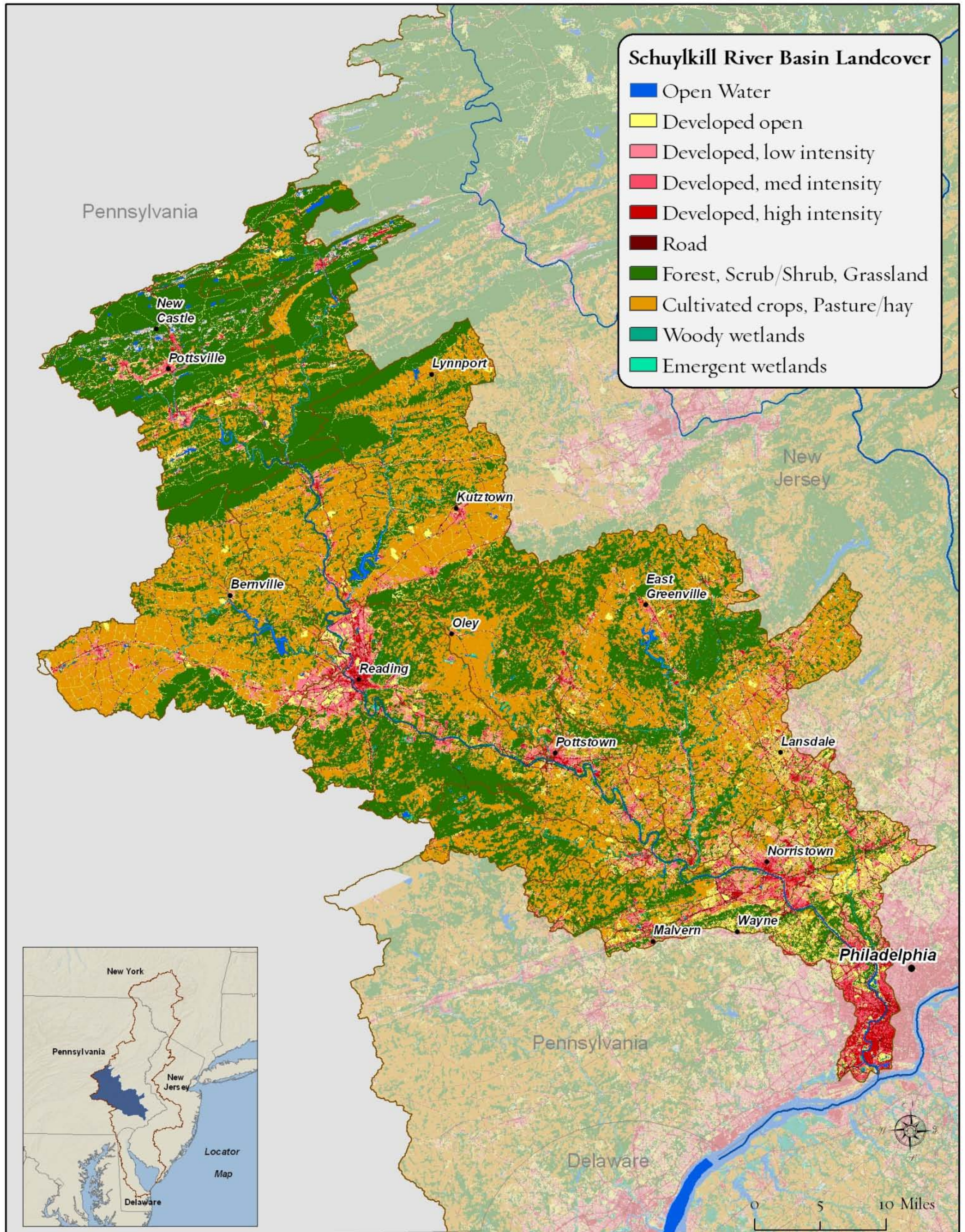


Figure 5.17. Land use in the Schuylkill River Basin

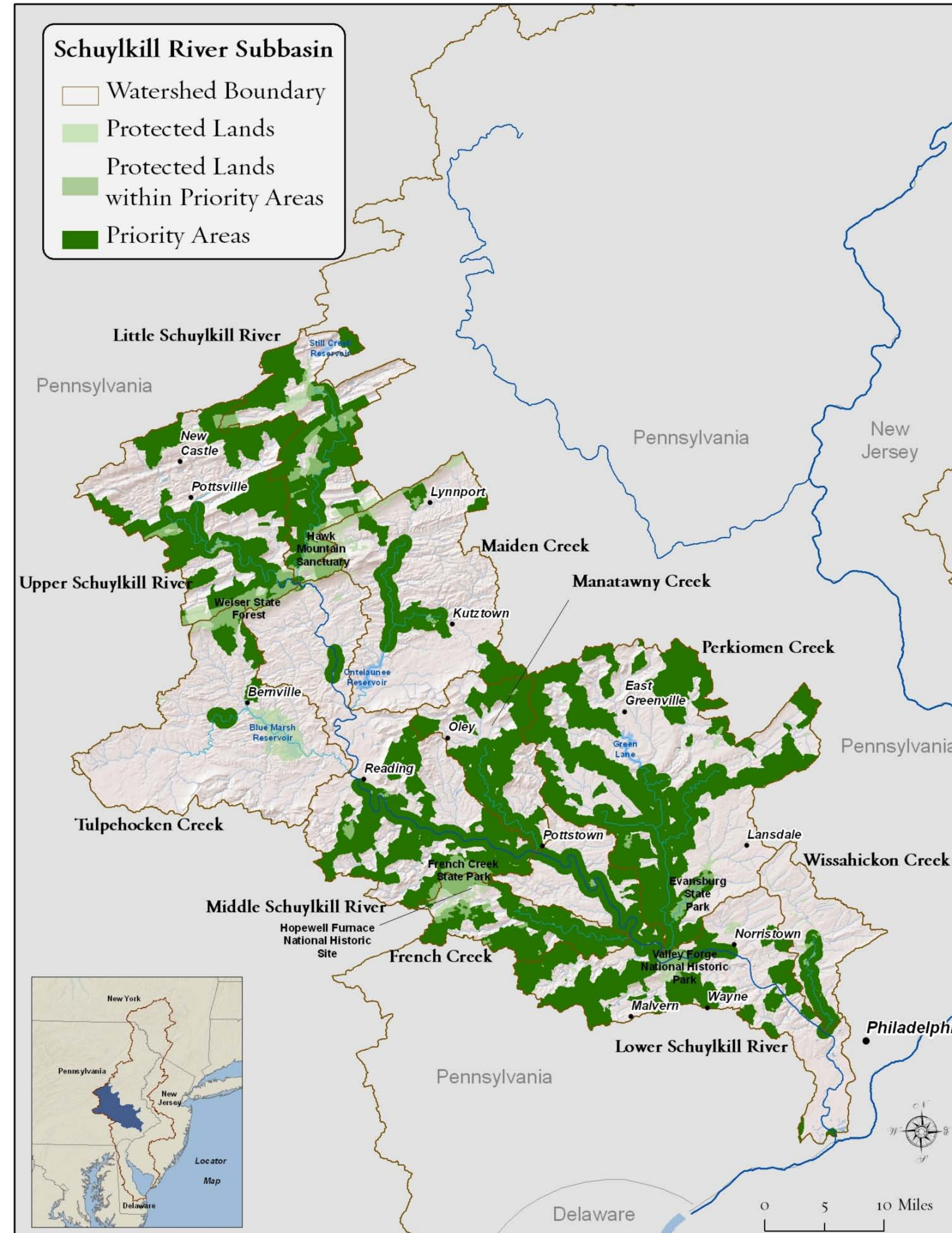


Figure 5.18. Protected lands in the Schuylkill River Basin

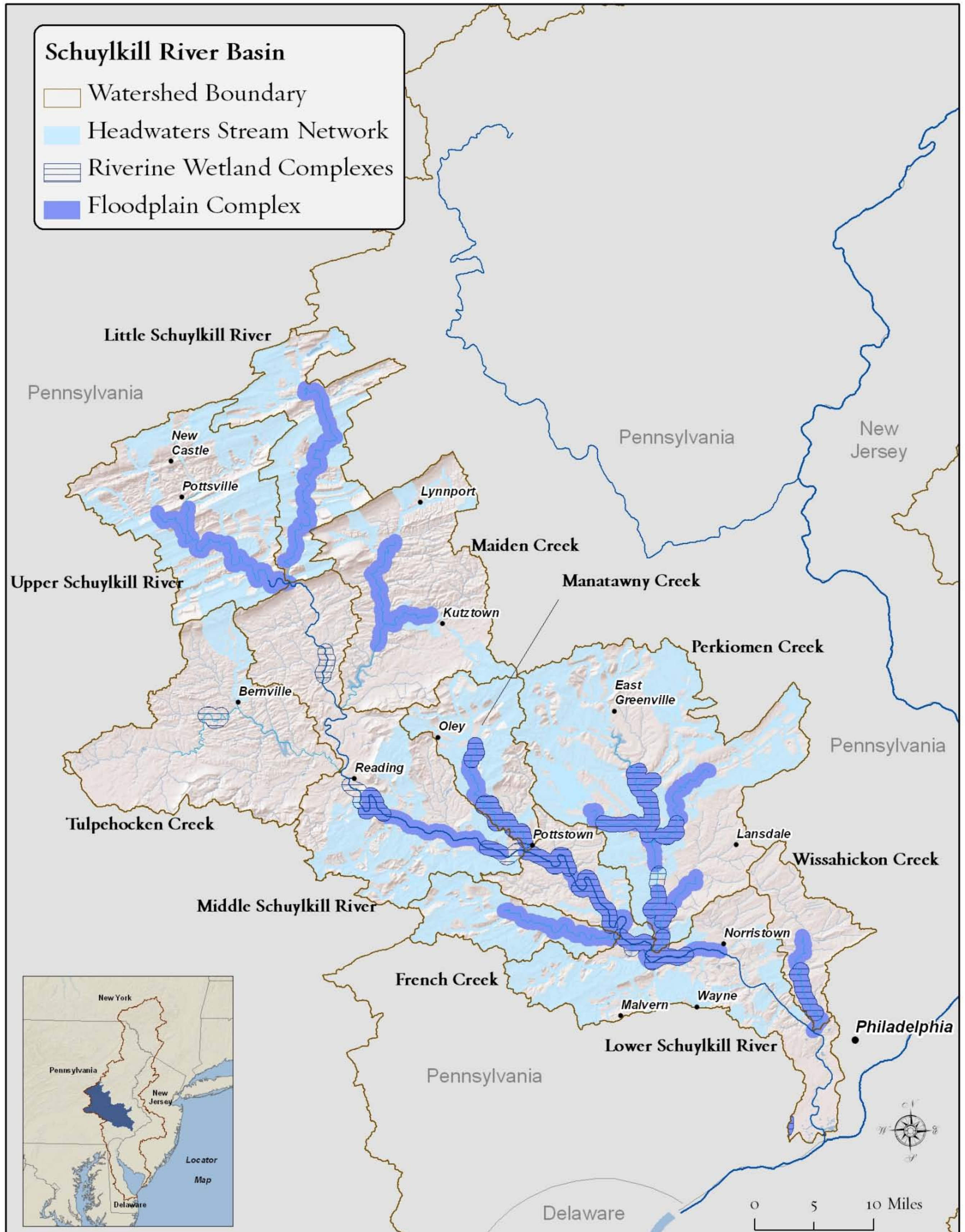


Figure 5.19. Priority conservation areas in the Schuylkill River Basin by ecosystem type

Watershed Name	Freshwater System Priorities	Priority Strategies				
		Forest Conservation	Wetland Conservation	Agricultural Land Protection and Conservation	Aquatic Connectivity Restoration	Streamflow Management
		F	W	A	C	D
Little Schuylkill River	Floodplain Complexes; Headwater Networks	●				●
Upper Schuylkill River	Floodplain Complexes; Headwater Networks	●			●	●
Maiden Creek	Floodplain Complexes; Headwater Networks	●		●		
Tulpehocken Creek	Headwater Networks; Riverine Wetlands	●		●		
Manatawny Creek	Floodplain Complexes; Headwater Networks; Headwater Wetlands; Riverine Wetlands	●	●	●	●	
Middle Schuylkill River	Floodplain Complexes; Headwater Networks; Headwater Wetlands; Riverine Wetlands	●	●	●		●
French Creek	Floodplain Complexes; Headwater Networks; Headwater Wetlands	●	●	●	●	
Perkiomen Creek	Floodplain Complexes; Headwater Networks; Headwater Wetlands; Riverine Wetlands	●	●	●	●	
Wissahickon Creek	Floodplain Complexes; Riverine Wetlands			●	●	
Lower Schuylkill River	Floodplain Complexes; Headwater Wetlands; Riverine Wetlands			●	●	●

Table 5.4. Freshwater priorities in Schuylkill River Basin by watershed

DELAWARE RIVER ESTUARY:

PRIORITY CONSERVATION AREAS AND STRATEGIES

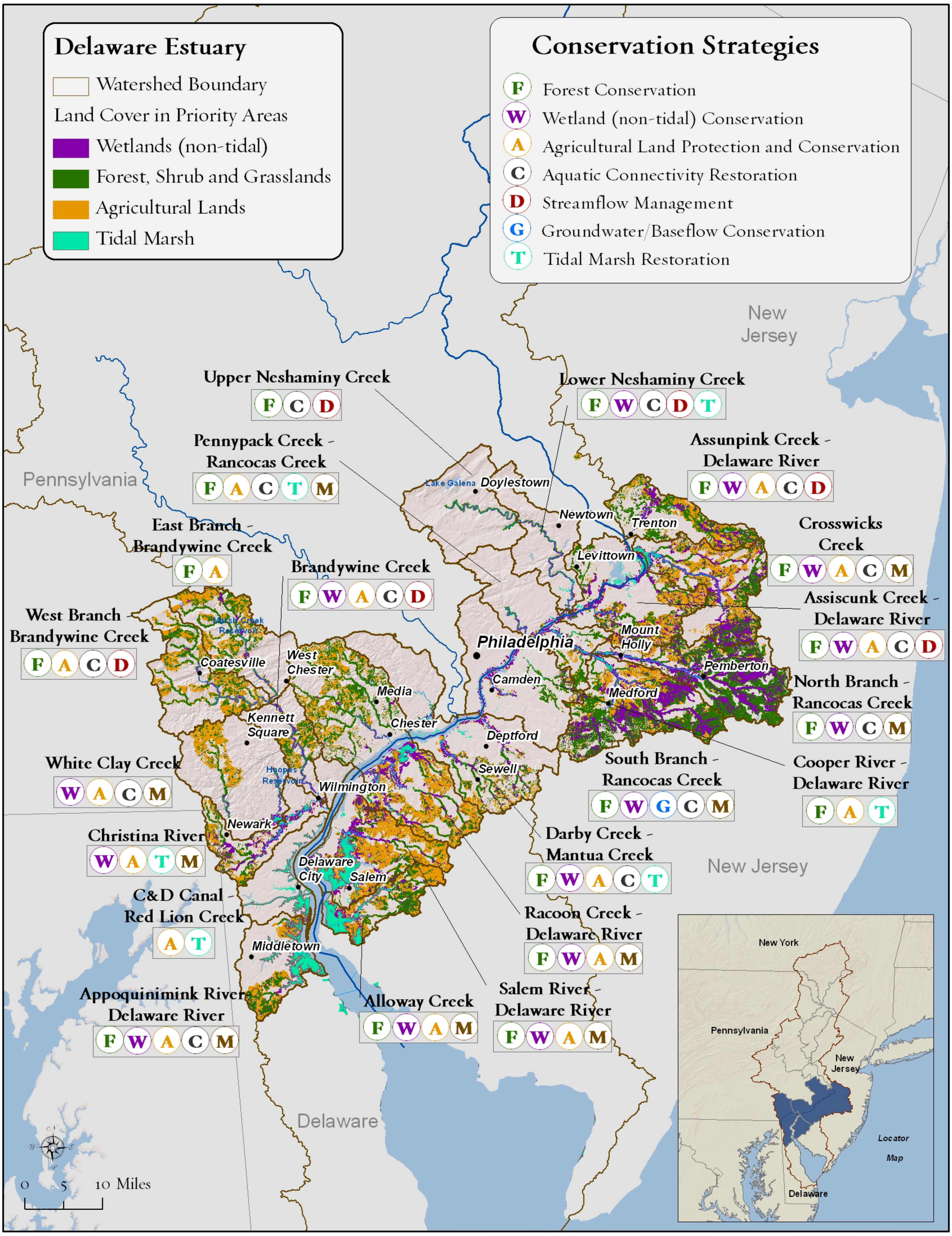


Figure 5.21. Priority conservation areas and recommended conservation strategies in the Delaware River estuary

The Delaware River Estuary

The Delaware River Estuary ~

The two estuary sub-basins of the Delaware River contain the entire tidal stretch of the mainstem Delaware River, from the head of tide at Trenton, NJ to where the river enters the bay near Wilmington, DE and Salem, NJ. Major tributaries include the Neshaminy Creek in Pennsylvania, the Brandywine Creek in Delaware, and the Rancocas Creek in New Jersey. In Pennsylvania and Delaware, this area includes the edge of the Piedmont and the Coastal Plain provinces; the latter province covers this area in New Jersey.

The estuary is home to the largest cities in Pennsylvania (Philadelphia) and New Jersey (Trenton). The Pennsylvania side of the estuary, the most densely populated area in the Delaware Basin, is highly developed compared to amounts of natural and agricultural cover in other portions of the basin (Figure 5.22); however, protected areas are still signifcant (Figure 5.23). Developed land cover is lower in DE and NJ than in PA, but this section is also the most developed in the basin on the New Jersey side. Brackish and salt marshes found in the downstream portion of the estuary, which provide especially critical habitat for species such as bottom-dwelling sturgeon, are less fragmented than the freshwater tidal marshes found upstream in the urban corridor.

Historically water quality in this stretch suffered so much from industrial and urban inputs that low dissolved oxygen formed an effective block to the migration of diadromous fish for much of the early 20th century; regulations and changed practices led to dramatic improvements in water quality in the late 1900s and a much-recovered river system today. However, the prevalence of urban land cover in this area makes the existing natural ecosystems all that more critical to maintaining function of the overall system and providing habitat for estuarine species.

The John Heinz National Wildlife Refuge contains important freshwater tidal wetlands in the Philadelphia area. Marsh Creek State Park in Pennsylvania, C&D Canal Wildlife Area in Delaware, Supawna Meadows National Wildlife Refuge in New Jersey, and Brendan T. Byrne State Forest in New Jersey are all additional significant protected areas. White Clay Creek, both its headwaters in Pennsylvania and its downstream portions in Delaware, is designated National Wild and Scenic.

Shortnose Sturgeon © Cody Meshes, USFWS

Anadromous Fish ~

For fish like river herring and American shad, this estuarine corridor provides critical access to further upstream spawning grounds in the non-tidal portions of the Delaware River Basin. For Atlantic sturgeon, this tidal stretch of the mainstem provides critical habitat for spawning, maturation, and feeding. Spawning occurs above the salt line up to near Trenton, and positive evidence of breeding (captured young-of-the-year) was noted in 2010, the first time in over 50 years. For federally endangered shortnose sturgeon, the estuarine stretch of the Delaware River is equally critical, as this species uses the river most intensively in the upstream portion of the estuary, even as far north as Lambertville, NJ. Important spawning areas occur between Scudder's Falls and the Trenton Rapids, and juveniles and foraging adults in summer use river stretches further downstream to Wilmington and Artificial Island. Maintaining habitat in all of these areas is an important strategy because of the limited availability of suitable habitat in the basin; ensuring good water quality and the existence of fringing freshwater tidal marshes over time through **marsh room-to-move protection** is one priority strategy to help protect diadromous fish like these sturgeon. **Restoring freshwater tidal marsh** in the urban corridor also is extremely important to maintain estuarine river quality.

Tidewater Mucket © A. Barlow

Freshwater Mussels ~

This undammed stretch of the mainstem Delaware also provides habitat for seven species of highly threatened freshwater mussels, including yellow lampmussel (*Lampsilis cariosa*), alewife floater (*Anodonta implicata*), and tidewater mucket (*Leptodea ochracea*). The latter species was previously thought to have been extirpated from this area of Pennsylvania, which emphasizes how critical the estuarine section of the Delaware River is for certain aquatic species. **Restoring freshwater tidal marsh** and **restoring aquatic connectivity** are important strategies in order to ensure that mussel populations can persist and continue to reproduce into the future.

Conservation Highlights ~

The map on the reverse (Figure 5.21) highlights watersheds within the estuary sub-basins where Forest Conservation, Wetland Conservation, Agricultural Land Protection and Conservation, Aquatic Connectivity Restoration, Streamflow Management, Groundwater/Baseflow, Tidal Marsh Restoration, Shoreline Conservation, and Marsh Room-to-Move Protection would help protect and restore basin biodiversity. In addition, Figure 5.24 illustrates the identified priority conservation areas within the estuary by ecosystem type, without associated land cover. Specific conservation strategy examples include:

Ⓒ Aquatic Connectivity Restoration

Opportunities exist for increasing fish passage in watersheds where barriers downstream on tributary rivers (near their confluence with the Delaware River) block the movement upstream of diadromous fish like shad, but often a suite of dam removals is required to open up significant habitat for fish. Efforts are underway to remove a series of dams along the downstream portion of **White Clay Creek** to help open up access for fish; allowing fish to pass through the locations of the first two dams will open up more than seven miles of habitat. Nearby, efforts are also ongoing to restore aquatic connectivity on the **Brandywine River**. Additional opportunities for barrier mitigation to increase the connectivity of rivers along significant floodplain complexes or of headwaters stream networks also occur in this stretch of the basin, including in the **Lower Neshaminy Creek**, **Crosswicks Creek**, **and North Branch-Rancocas Creek**. For freshwater tidal marsh, dams also can block migration of a marsh upstream and can disrupt natural water flow and sedimentation, affecting marsh accretion and condition. Dams most likely to be affecting freshwater tidal marshes (and thus for which mitigation measures should be a priority) occur in the **Appoquinimink River-Delaware River**, **Lower Neshaminy Creek**, **and Crosswicks Creek watersheds**.

Ⓣ Tidal Marsh Restoration

The urban and industrial landscape of the Delaware Estuary has severely degraded freshwater tidal marshes, reducing wildlife habitat and negatively affecting water quality. Due to the loss of freshwater tidal marshes and the ecosystem benefits they provide, increasing tidal marsh acreage in the most highly developed urban area in the basin is a priority strategy. Watersheds identified for tidal marsh restoration or creation in the estuary include the **Christina River**, **C&D Canal-Red Lion Creek**, **Darby Creek,** and the **Cooper River watersheds**. Above Philadelphia and Trenton, the **Lower Neshaminy Creek** watershed is a priority for freshwater tidal marsh restoration. The Pennsylvania Environmental Council and Philadelphia Water Department Office of Watersheds mapped and assessed freshwater tidal marshes along approximately 8 miles of the Delaware River in North Philadelphia to identify existing wetland areas, wetland enhancement areas, and potential wetland creation areas (PEC 2009). (Figure 5.25).

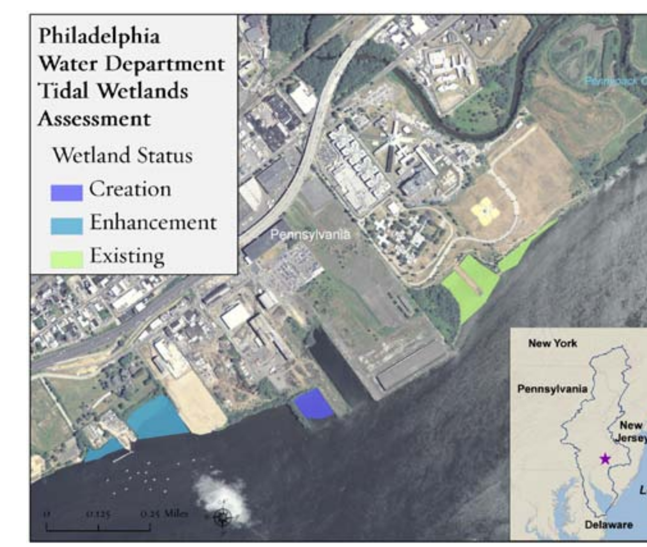


Figure 5.25. Freshwater tidal marshes along the Delaware River

Ⓜ Marsh Room-to-Move

The lower estuary contains the northern-most extent of brackish tidal marshes, ending at the C&D Canal in Delaware and the Salem River in New Jersey. The brackish tidal marshes in the **Appoquinimink River** and **Salem River** watersheds are adjacent to natural lands that should be protected to allow for marsh migration as sea levels rise. In the future, freshwater tidal marshes also may require adjacent natural lands for marsh migration. Protecting natural lands adjacent to freshwater tidal marshes is a priority strategy in the **White Clay Creek** and the **Christina River** in Delaware, and the **North Branch of Rancocas Creek**, **Raccoon Creek**, **and Alloway Creek** in New Jersey. Raccoon Creek contains a large freshwater tidal marsh with adjacent natural lands that, if protected, will allow for upstream marsh migration as sea levels rise.

Ⓕ Forest Conservation Ⓦ Wetland Conservation Ⓐ Agricultural Land Protection and Conservation

Opportunities for forest, wetland, and agricultural conservation in headwaters, floodplains, and wetlands occur throughout this region but are most abundant in the New Jersey Coastal Plain. Forested headwaters play a critical role in maintaining watershed condition downstream, including the tidal marshes that characterize this section of the basin and the important concentrations of non-tidal wetlands that occur both in headwaters and floodplains. Protecting and managing forests, wetlands, and surrounding agricultural areas for ecological value applies to significant areas in the **North and South Branch Rancocas Creek**, **Raccoon Creek-Delaware River**, **Crosswicks Creek**, **and Salem River-Delaware River Watersheds**.

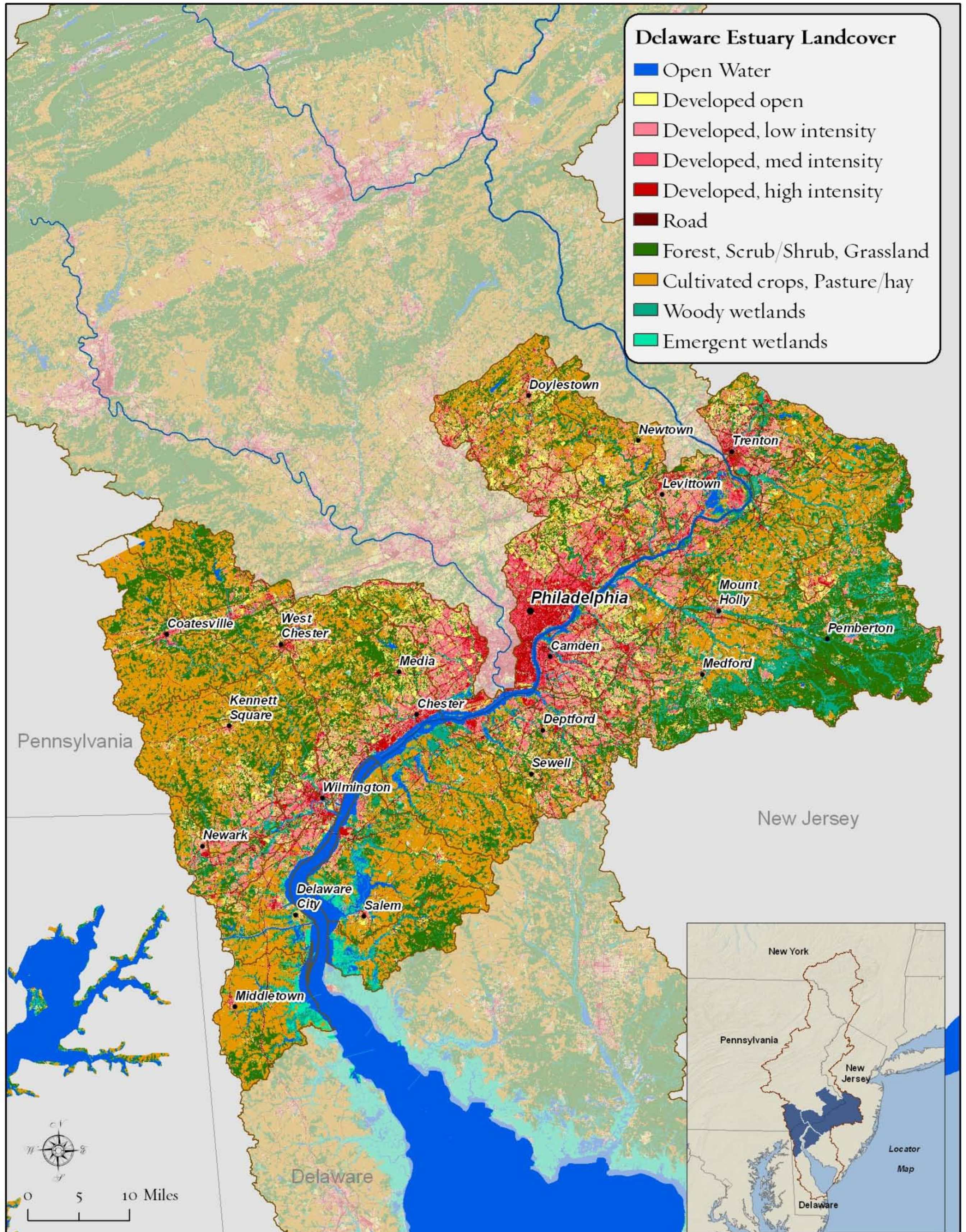


Figure 5.22. Land use in the Delaware River Estuary

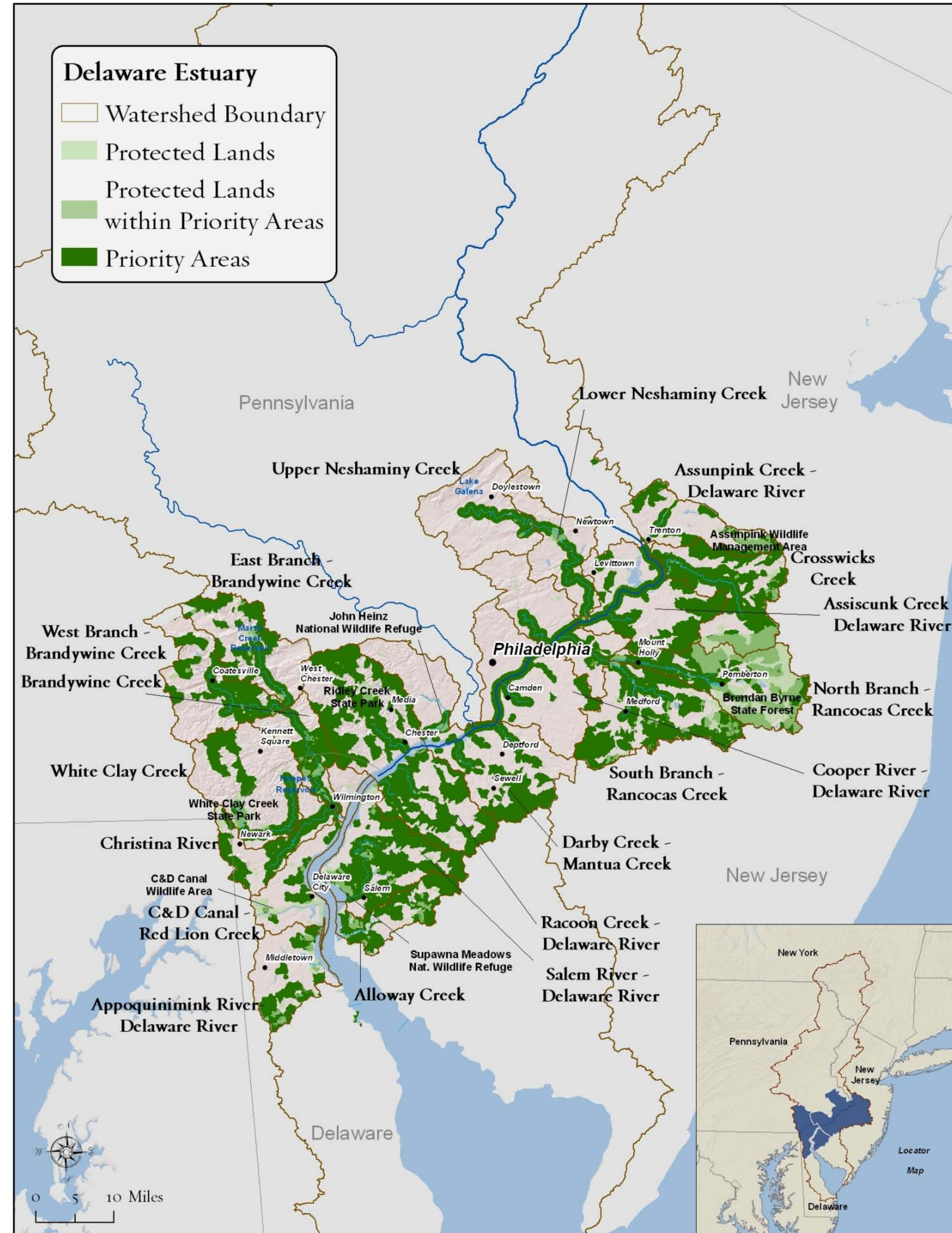


Figure 5.23. Protected Lands in the Delaware River Estuary

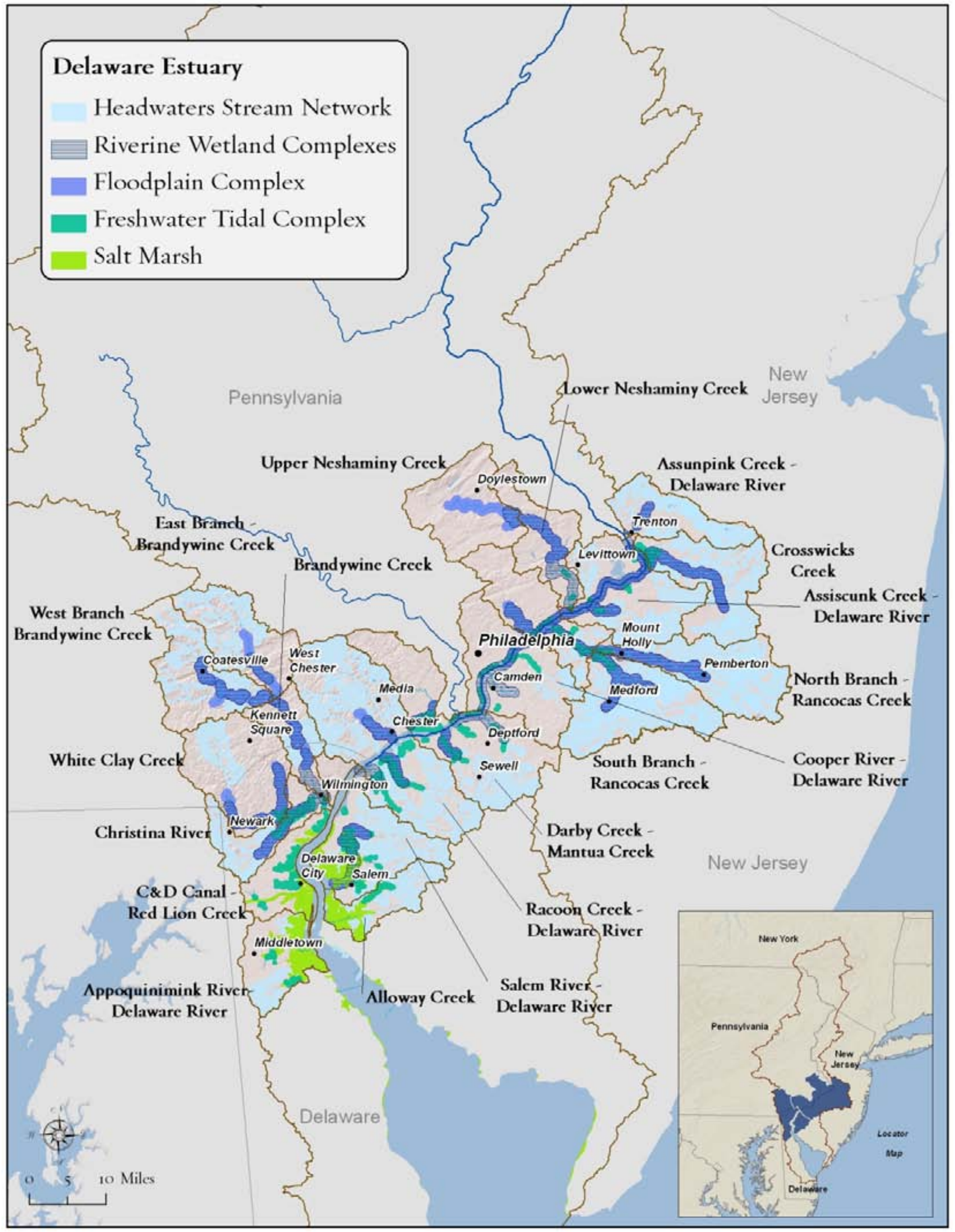


Figure 5.24. Priority conservation areas in the Delaware River Estuary by ecosystem type

Watershed Name	Freshwater and Tidal System Priorities	Priority Strategies							
		Forest Conservation	Wetland Conservation	Agricultural Land Protection and Conservation	Aquatic Connectivity Restoration	Streamflow Management	Groundwater/ Baseflow Conservation	Tidal Marsh Restoration	Marsh Room-to-Move Protection
		F	W	A	C	D	G	T	M
Upper Neshaminy Creek	Floodplain Complexes	●			●	●			
Lower Neshaminy Creek	Floodplain Complexes; Freshwater Tidal Marshes	●	●		●	●		●	
Assunpink Creek-Delaware River	Floodplain Complexes; Headwater Networks	●	●	●	●	●			
Crosswicks Creek	Floodplain Complexes; Headwater Networks; Freshwater Tidal Marshes	●	●	●	●				●
Assiscunk Creek-Delaware River	Floodplain Complexes; Headwater Networks; Freshwater Tidal Marshes	●	●	●	●	●			
North Branch Rancocas Creek	Floodplain Complexes; Headwater Networks; Freshwater Tidal Marshes	●	●		●				●
South Branch Rancocas Creek	Floodplain Complexes; Headwater Networks; Freshwater Tidal Marshes	●	●		●	●	●		●
Pennypack Creek-Rancocas Creek	Floodplain Complexes; Headwater Networks; Freshwater Tidal Marshes	●		●	●			●	●
Cooper River-Delaware River	Freshwater Tidal Marshes							●	
Darby Creek-Mantua Creek	Floodplain Complexes; Headwater Networks; Freshwater Tidal Marshes	●	●	●	●			●	
Raccoon Creek-Delaware River	Floodplain Complexes; Headwater Networks; Freshwater Tidal Marshes	●	●	●					●
Salem River-Delaware River	Floodplain Complexes; Headwater Networks; Freshwater Tidal Marshes; Salt Marshes	●	●	●					●
Alloway Creek	Headwater Networks; Freshwater Tidal Marshes; Salt Marshes	●	●	●				●	●
East Branch Brandywine Creek	Headwater Networks	●		●					
West Branch Brandywine Creek	Floodplain Complexes; Headwater Networks	●		●	●	●			
Brandywine Creek	Floodplain Complexes; Headwater Networks	●	●	●	●	●			
White Clay Creek	Floodplain Complexes; Headwater Networks; Freshwater Tidal Marshes		●	●	●				●
Christina River	Floodplain Complexes; Headwater Networks; Freshwater Tidal Marshes		●	●				●	●
C&D Canal-Red Lion Creek	Freshwater Tidal Marshes			●				●	
Appoquinimink River-Delaware River	Headwater Networks; Freshwater Tidal Marshes; Salt Marshes	●	●	●	●				●

Table 5.5. Freshwater and tidal priorities in Delaware River Estuary by watershed

DELAWARE BAY SUB-BASIN:

PRIORITY CONSERVATION AREAS AND RECOMMENDED STRATEGIES

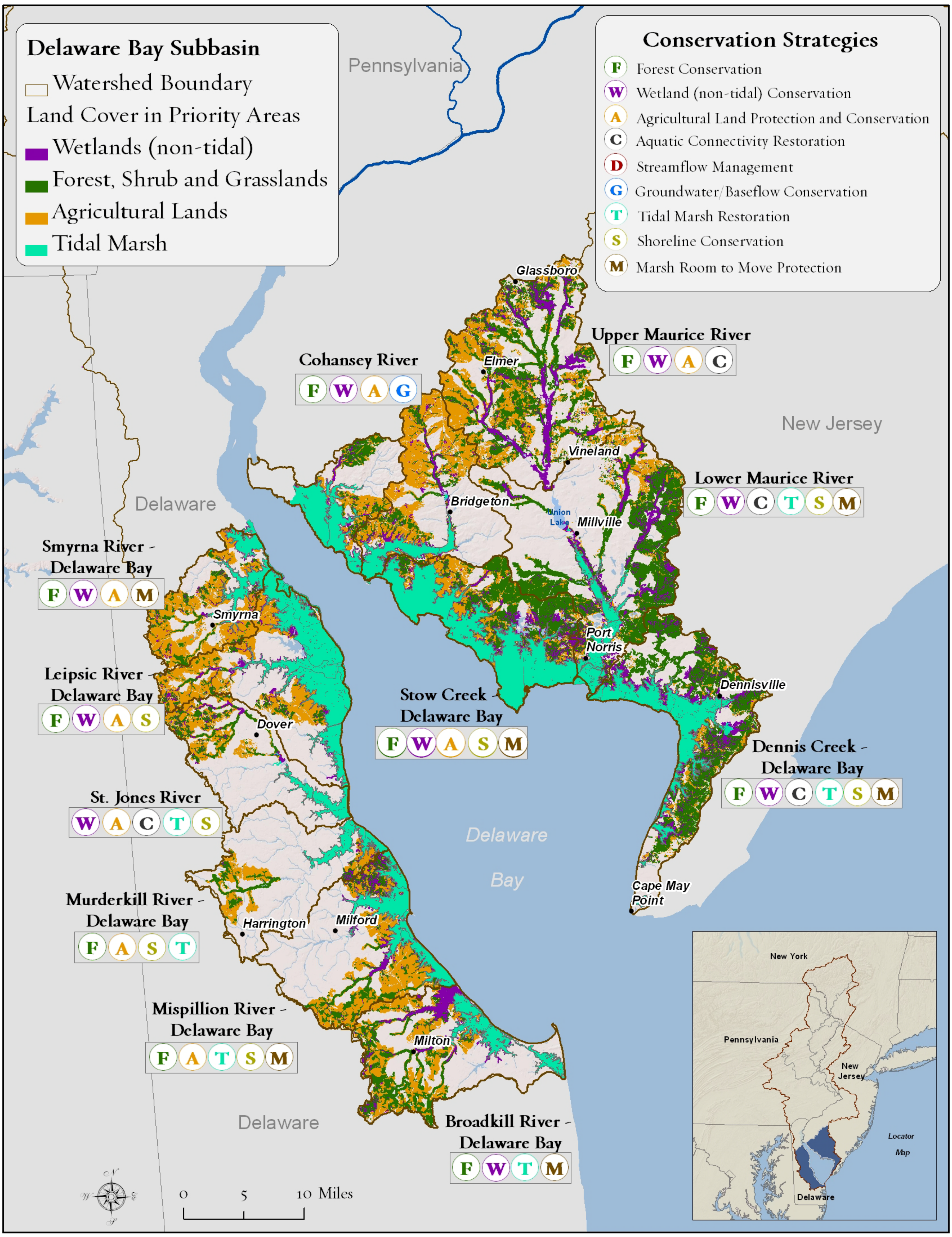


Figure 5.26. Priority conservation areas and recommended conservation strategies for the Delaware Bay sub-basin

The Delaware Bay Sub-Basin

The Delaware Bay Sub-Basin ~

The Delaware Bay sub-basin is located in the lower salt water and brackish tidal portion of the Delaware River Basin. This sub-basin is distinguished by a contiguous band of salt and brackish tidal marshes that extends around the Delaware Bay (Figure 5.27). In addition to critical salt and brackish tidal marshes, non-tidal habitats also play a key role in the biodiversity of the Delaware Bay. In addition to providing habitat for terrestrial species, forests in the Delaware Bay protect water quality for aquatic species, especially in the headwaters and floodplains of the rivers and streams that flow into the bay. Small tidal freshwater systems occur at some of the upper reaches of the tide, and a few large freshwater river systems occur in the sub-basins that drain directly into the Delaware Bay. The majority of the Delaware Bay landscape is forested in New Jersey and is agricultural in Delaware. The few population centers in the Delaware Bay occur in Millville and Vineland, NJ and in Dover and Milford, DE.

Approximately 244,000 acres of land in the Delaware Bay sub-basin is protected (Figure 5.28). The Maurice River in New Jersey is a federally-designated Wild and Scenic River. U.S. Fish and Wildlife Service National Wildlife Refuges within the Delaware Bay include Prime Hook, Bombay Hook, and Cape May. PSEG's Estuary Enhancement Program (EEP) has restored and protected approximately 32 square miles of coastal wetlands and adjacent uplands along the Delaware Bay. The Delaware Bay is also a part of the Delaware Estuary National Estuary Program, one of 28 across the United States.

The species distributions in the Delaware Bay are driven by salinity that decreases in concentration from the mouth of Delaware Bay to where the bay's waters meet the Delaware River at New Castle, DE and Salem, NJ. Alewife (*Alosa pseudoharengus*) and other diadromous fish move through the bay to spawning grounds in the mainstem Delaware River and the many rivers and streams that drain directly into the bay. Removing barriers on alewife spawning rivers could benefit alewife in the Delaware Bay significantly. The blue crab (*Callinectes sapidus),* an aquatic species important both ecologically and commercially, breeds and feeds along the tidal marshes.

Black Duck~

Wetlands of the Delaware Bay support the largest concentration of overwintering black ducks in the world, while the Delaware River Basin provides both black duck breeding and migratory stopover habitats.

The **tidal marsh restoration** strategy will increase valuable habitat for black ducks, while the **marsh room-to-move** protection strategy will help ensure the continued existence of tida marsh habitat in the future by allowing marshe to move inland as sea levels rise. **Forest and wetland conservation** strategies will protect and restore black duck habitat inland of tidal marshes.

Red knots and horseshoe crabs on New Jersey beach. ©TNC staff

Migratory Shorebirds, such as the red knot (*Calidris canutus rufa)*, use the Delaware Bay as a critical stopover area during spring migration. The shorebirds arrive at the bay just as horseshoe crab (*Limulus polyphemus)* spawning begins, and they feed on the abundance of eggs deposited by crabs on bay beaches. Recent shorebird population declines are linked to declines in spawning horseshoe crabs in the Delaware Bay (McGowan et al. 2011). Therefore, protecting and restoring Delaware Bay beaches is important for conservation of both the horseshoe crab and migratory shorebirds. **Shoreline conservation strategies** include the protection of natural beaches and the restoration of degraded beaches. The bay's characteristic tidal marshes provide nesting grounds for avian species like the black duck (*Anas rubripes*) and saltmarsh sparrow (*Ammodramus caudacutus*).

Conservation Highlights ~

The map on the reverse (Figure 5.26) highlights sub-watersheds within the bay sub-basin where Forest Conservation, Wetland Conservation, Agricultural Land Protection and Conservation, Aquatic Connectivity Restoration, Streamflow Management, Groundwater/Baseflow, Tidal Marsh Restoration, Shoreline Protection, and Marsh Room-to-Move Protection would help protect and restore basin biodiversity. In addition, Figure 5.29 illustrates the identified priority conservation areas within the sub-basin by ecosystem type, without associated land cover. Specific conservation strategy examples include:

F W G **Forest and Wetland Conservation and Groundwater/Baseflow Conservation:** While the NJ and DE landscapes differ, forest conservation is a priority strategy in most watersheds in the Delaware Bay. In New Jersey, the Pinelands Conservation Fund could be used to acquire forests within the Pinelands boundaries. Important concentrations of non-tidal wetlands occur both in headwaters areas and within the riverine wetland complexes associated with larger floodplains. The **Cohansey River** watershed in the Delaware Bay ranked as one where conserving groundwater is likely to be a key strategy in protecting the health of headwater stream networks**.** A variety of actions, such as managing land use and protecting and restoring forests in high recharge areas, will be important to undertake as part of the groundwater/baseflow strategy.

A **Agricultural Land Protection and Conservation:** Maintaining and managing agricultural areas, especially where they surround headwater or riverine wetlands, is a critical conservation strategy that is especially important in watersheds where significant acreage of wetlands and agriculture coincide: the **Lower Maurice River, Upper Maurice River, Cohansey River, Stow Creek, Saint Jones River, Mispillion River, Murderkill River, Leipsic River, Smyrna River.** Where agricultural lands fall within the tidal marsh room-to-move lands, agricultural land protection and conservation strategies aim to protect agricultural lands from development in order to allow for marsh migration in both Delaware and New Jersey.

Tidal Marsh Restoration: Low elevation tidal marshes in this sub-basin are vulnerable to the effects of sea level rise and are priorities for strategies to enhance elevation to mitigate these effects. Utilizing elevation models, we identified the **Dennis Creek, Lower Maurice River, Mispillion River, Saint Jones River, Murderkill River, and Broadkill River** watersheds to be priorities for tidal marsh restoration in the sub-basin because of the presence of low elevation marshes. Example actions that could take place in these areas include utilizing natural infrastructure at the bay-marsh fringe and sediment management on marsh surfaces. Opportunities for tidal marsh restoration exist within the U.S. Army Corps of Engineers Regional Sediment Management Program. The PSEG tidal marsh restoration projects present an example of large scale restoration in the sub-basin.

S **Shoreline Conservation**

Natural beaches occur throughout the sub-basin, providing important habitat for spawning horseshoe crabs and foraging opportunities for migratory shorebirds. The remains of abandoned towns on the bay shore have degraded certain beaches and now present opportunities for restoration. Example opportunities occur in the **Dennis Creek** watershed at Thompson's Beach and Moore's Beach, and in the Maurice River cove within the **Lower Maurice River** watershed. In Delaware, the **Mispillion River** and **Murderkill River** watersheds require beach replenishment and restoration for horseshoe crabs and shorebirds.

M **Marsh Room-to-Move Protection**

Protecting natural lands adjacent to tidal marshes to allow for marsh migration as sea levels rise can be undertaken through fee acquisition, conservation easement, or private-lands management. In New Jersey, the **Dennis Creek** (6,518 acres in room-to-move/50% unprotected) (Figure 5.30), **Lower Maurice River** (2,428 acres in room-to-move/65% unprotected), and **Stow Creek** (5,771 acres in room-to-move/54% unprotected) watersheds are priorities for marsh room-to-move protection. In Delaware, the **Mispillion River** (5,998 acres in room-to-move/83% unprotected), **Broadkill River** (3,418 acres in room-to-move/90% unprotected), and **Smyrna River** (4,881 acres in room-to-move/79% unprotected) are priorities for tidal marsh room-to-move protection. In New Jersey, the Pinelands Conservation Fund could be used to acquire marsh room-to-move lands that fall within the boundaries of the Pinelands National Reserve. The Dennis Creek and Maurice River watersheds contain portions of the Pinelands within their boundaries.

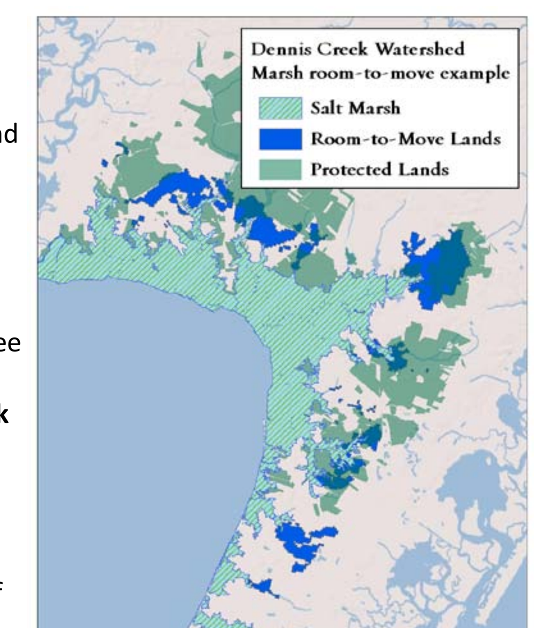


Figure 5.30. Marsh room-to-move example in the Dennis Creek, NJ watershed.

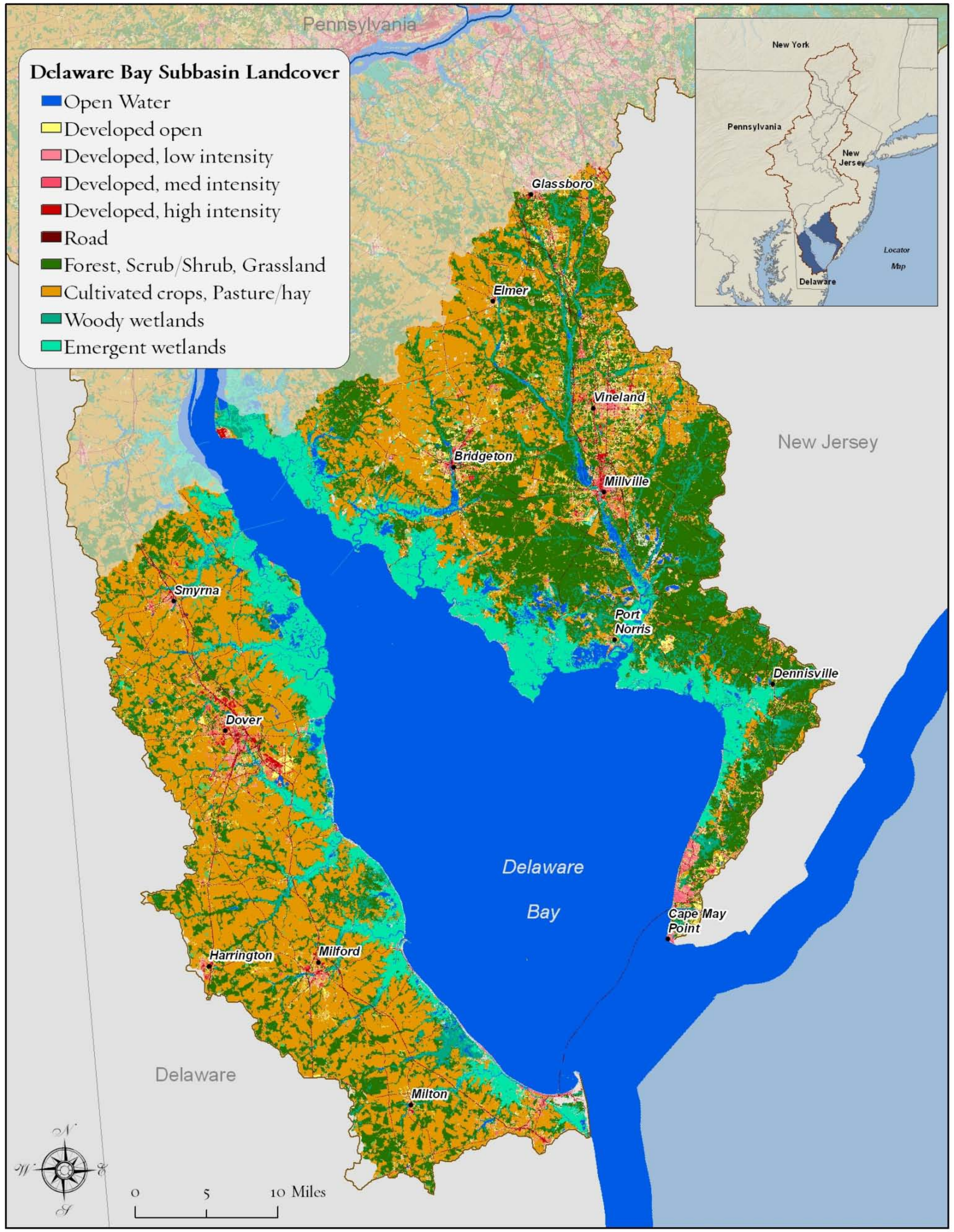


Figure 5.27. Land use in the Delaware Bay sub-basin

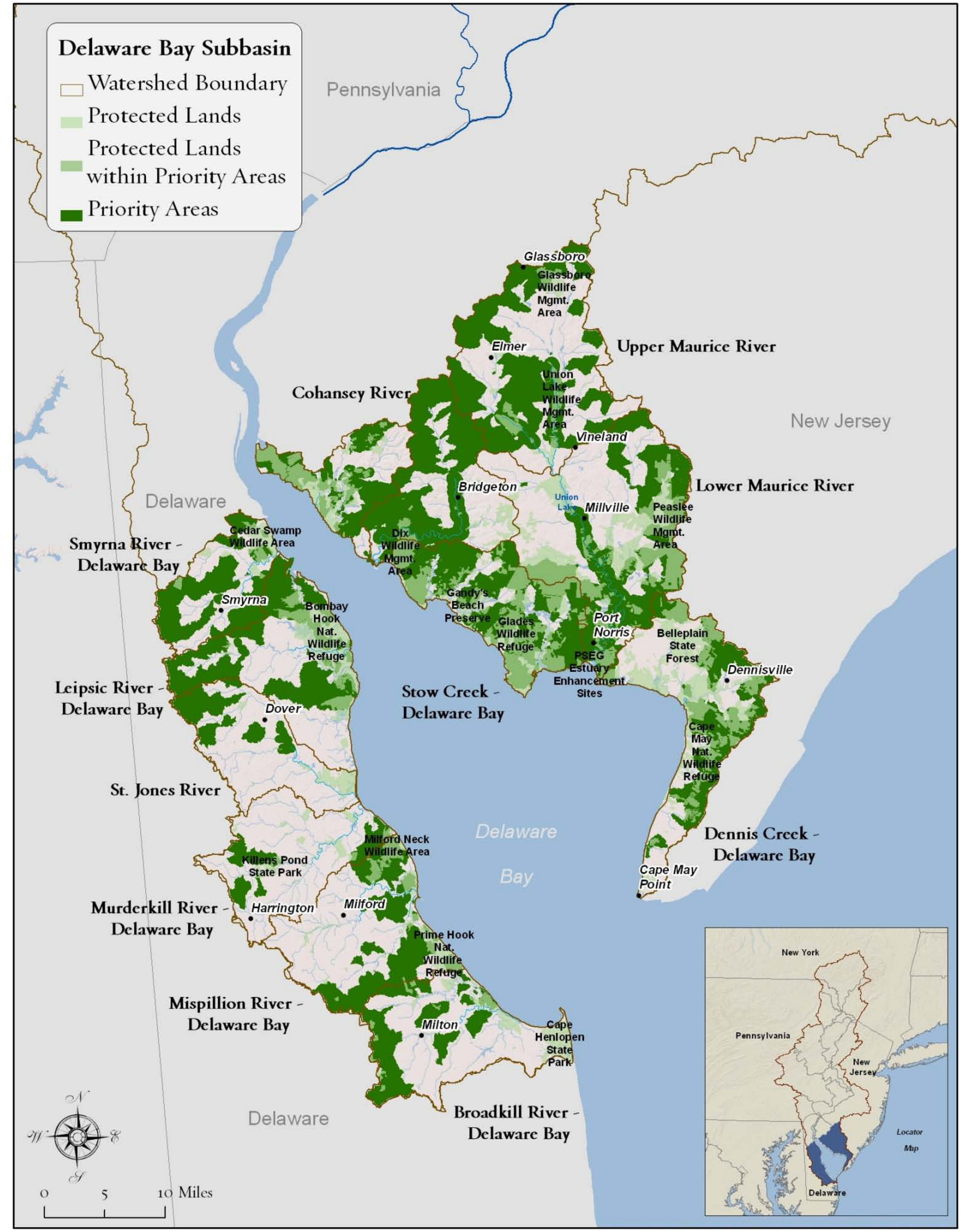


Figure 5.28. Protected lands in the Delaware Bay sub-basin

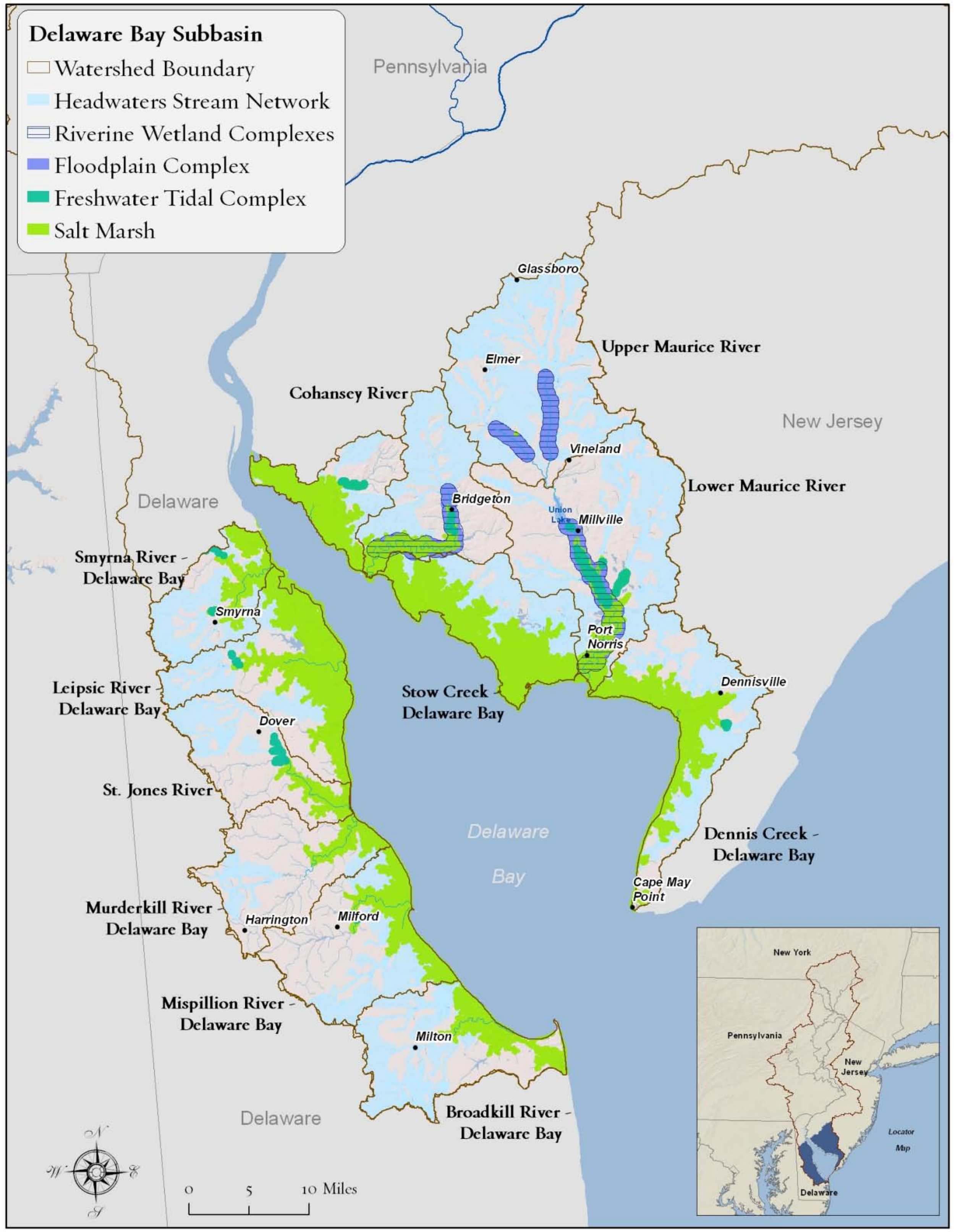


Figure 5.29. Priority conservation areas in the Delaware Bay sub-basin by ecosystem type

Watershed	Freshwater and Tidal System Priorities	Priority Strategies							
		Forest Conservation	Wetland Conservation	Agricultural Land Protection and Conservation	Aquatic Connectivity Restoration	Groundwater /Baseflow Conservation	Tidal Marsh Restoration	Shoreline Conservation	Marsh Room-to-move Protection
		F	W	A	C	G	T	S	M
Cohansey River	Floodplain Complexes; Headwater Networks; Salt marshes	●	●	●		●			
Stow Creek	Floodplain Complexes; Freshwater Tidal marshes; Salt Marshes	●	●	●				●	●
Upper Maurice River	Floodplain Complexes; Headwater Networks; Salt marsh	●	●	●	●				
Lower Maurice River	Floodplain Complexes; Headwater Networks; Freshwater Tidal Marshes; Salt marshes	●	●				●	●	●
Dennis Creek	Headwater Networks; Freshwater Tidal Marshes; Salt Marshes	●	●		●		●	●	●
Smyrna River	Headwater Networks; Freshwater Tidal Marshes; Salt Marshes	●	●	●					●
Leipsic River	Headwater Networks; Freshwater Tidal Marshes; Salt Marshes	●	●	●				●	
St. Jones River	Headwater Networks; Freshwater Tidal Marshes; Salt Marshes		●	●	●		●	●	
Murderkill River	Headwater Networks; Salt Marshes	●		●			●	●	
Mispillion River	Headwater Networks; Salt Marshes	●		●			●	●	●
Broadkill River	Headwater Networks; Salt Marshes	●	●				●		●

Table 5.6. Freshwater and tidal priorities in Delaware Bay sub-basin by watershed

Recommended Oyster Conservation Areas with Tactics

Marine Bivalve Priority Area 1: High Productivity Oyster Beds

The "central beds" of the oyster seed beds (appearing in pink), which have the highest productivity since the onset of oyster diseases, include Shell Rock, Upper Middle, Middle, Ship John, Cohansey, and Sea Breeze. These central beds achieve the highest productivity because of their strategic position in the system: they are far enough south to take advantage of high food quality and relatively consistent recruitment, and far enough north to escape high disease mortality. While disease is even lower in the upper beds, food quality and recruitment there are lower, resulting in slower growth and sporadic recruitment (Figure 5.31). Strategies proposed in this central region of the bay aim to keep these beds at a highly productive level, which is imperative to sustaining both a commercial fishery and overall population abundance. Currently, shell planting is a major tactic being employed in this area, in part using funding from the Oyster Restoration Task Force. Other recommended strategies for Area 1 can be found in Table 5.7.

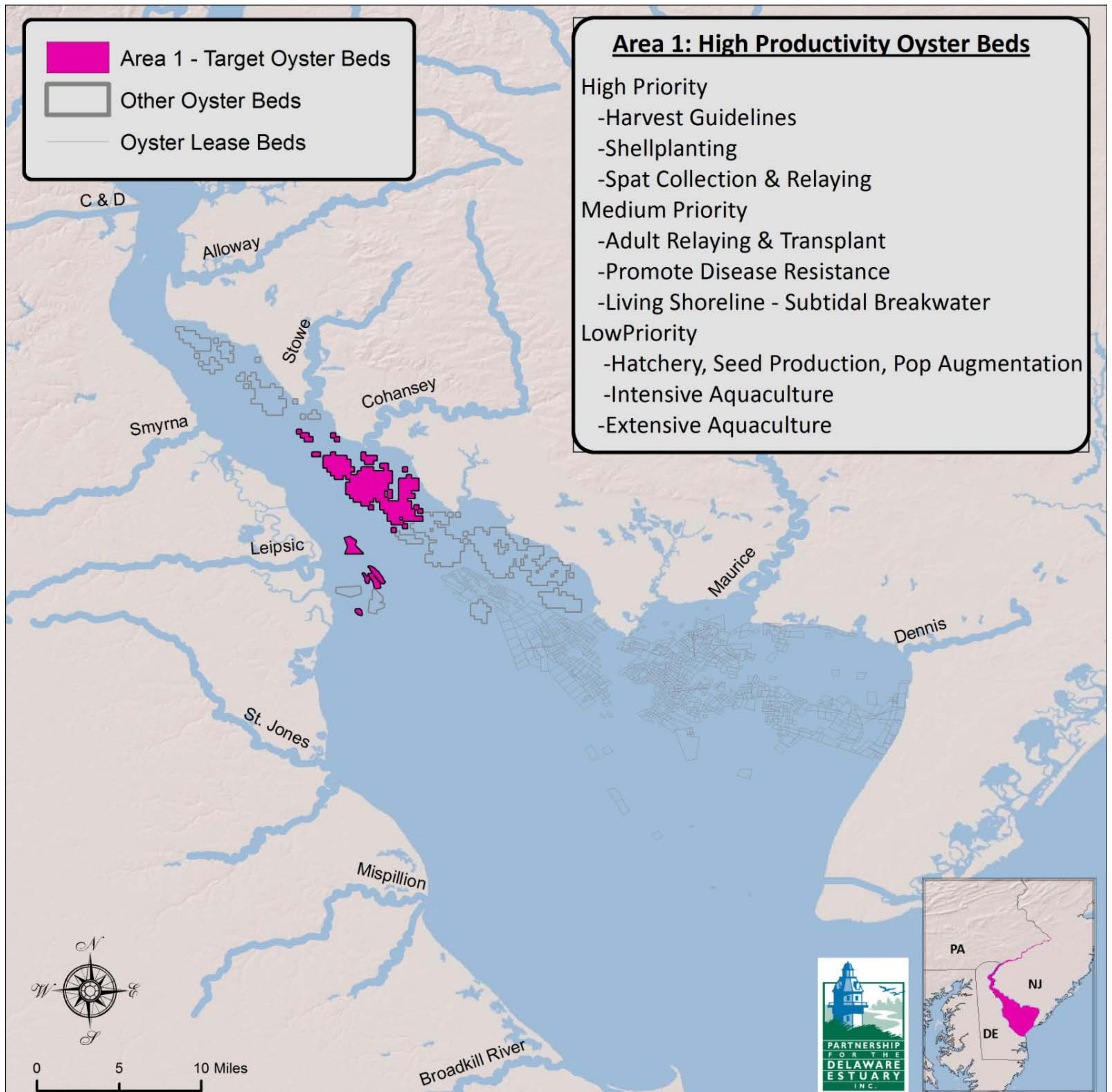


Figure 5.31. Area 1: High productivity oyster beds in the Delaware Bay

High Priority		Medium Priority		Low Priority	

HG **Harvest Guidelines**
Harvest guidelines, aimed at keeping the middle beds highly productive, . should continue to rely on annual monitoring surveys and science-based adaptive management by the Shellfish Advisory Committee.

SP **Shell Planting**
Shell planting maintains and increases extant populations by enhancing natural recruitment and replacing shell lost to natural erosion or harvesting. Target areas should ideally have a good probability of recruitment and relatively high survival and growth.

SR **Spat Collection & Relaying**
Shell planting in the lower bay where recruitment is high but survival is low can be an effective strategy for collecting young oysters before they die and moving them to more productive areas for grow-out, e.g., collect spat on shell from Cape Shore and move it to Area 1.

AR **Adult Relaying & Transplant**
Adult oysters can be collected from areas of low survivorship or low productivity and transplanted to areas of high productivity and moderately low mortality, such as the central beds. Movement of adults from the very low mortality (upper) beds should be carefully considered and monitoring and research are needed to understand shell and oyster population maintenance on these beds. Because recruitment is usually low on the upper beds, planting of spat on shell (either from the hatchery or natural set) should be considered here, possibly using disease-resistant stocks. In any case, shell replacement must be considered from source areas.

DR **Promote Disease Resistance**
Enhancing oyster populations in medium and high disease zones encourages the breeding of disease-resistant oysters. Funding is needed to sustain disease resistance research and monitoring in relation to managing Area 1.

LSB **Living Shoreline – Subtidal Breakwater**
A subtidal nearshore oyster breakwater is recommended as a pilot project in Area 1. If effective, this approach could then be expanded to other places. The shallow waters bordering Sea Breeze are a candidate test location since this is a marginal area where oyster harvesting is reportedly difficult. Subtidal oyster breakwaters might also be constructed as part of a hybrid tactic combined with living shorelines.

HS **Hatchery, Seed Production, Population Augmentation**
Oysters can be grown in a hatchery and transplanted to the middle beds to increase oyster abundance in the high-productivity Area 1. However, this tactic is assigned low priority as long as collection of natural spat remains less expensive and effective.

AI **Intensive Aquaculture**: This could not be conducted in this area without significant changes in regulations

AE **Extensive Aquaculture**: This could not be conducted in this area without significant changes in regulations

Table 5.7. Recommended tactics for Area 1 - High Productivity Oyster Beds.

Marine Bivalve Priority Area 2: Marginal (Harvest) Area Targets

Marginal (harvest) areas (Figure 5.32) are defined as areas which are not as good for oyster harvest for one of four reasons: 1) the area is too shallow for oyster boats to get into, 2) the bottom is rocky or sparse in shell cover, 3) oysters are in tributaries that are closed to harvest, or 4) the area has high disease pressure. Since most of these areas are included in area management planning, care must be taken to work with the Stock Assessment Reivew Committee. Marginal harvest areas have potential to be prime areas for conservation or ecological restoration. Marginal areas that cannot be effectively dredged for commercial harvests due to depth or bottom conditions (#1 and 2 above) might represent places to install shallow subtidal, nearshore reefs. There are several places along the New Jersey Bayshore where historic oyster reefs were reported that could be candidates for nearshore oyster reef enhancemen - denoted as green stars in Figure 5.32. Some of these locations are located in NJDEP prohibited or special restricted waters for shellfish (NJDEP 2011), which could necessitate use of construction tactics that thwart poaching. In addition, tongers might still work some of these shallow nearshore marginal areas, and more (local) research would be needed to determine if these users would be affected. Additional opportunities exist in Delaware waters near the mouth of the Leipsic, St. Jones, or Murderkill Rivers in suitable nearshore marginal areas.

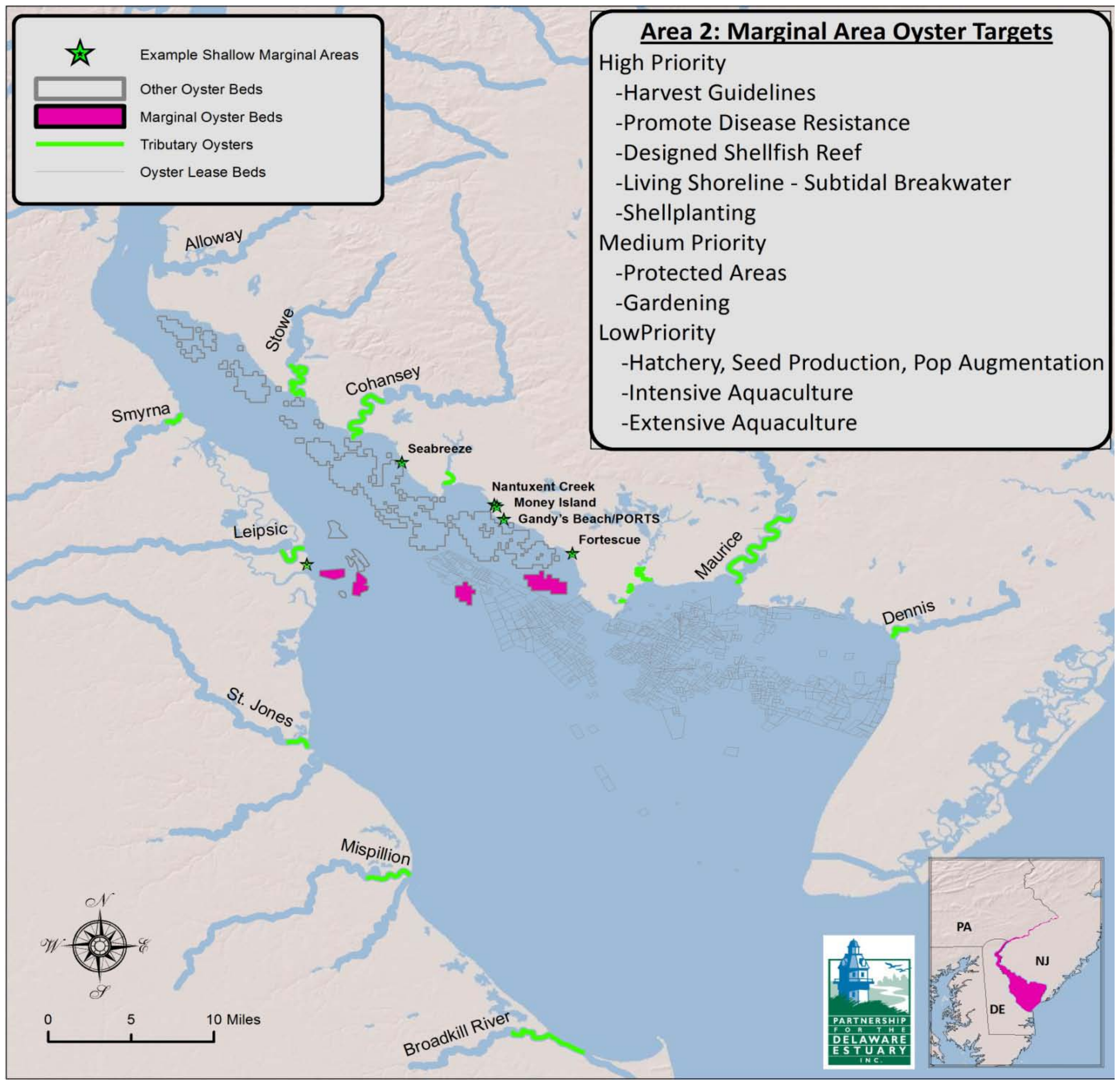


Figure 5.32. Area 2: Marginal (harvest) areas in the Delaware Bay

*<u>High disease marginal areas</u> include the beds of **Ledge and Egg Islands**. Although disease pressure is high on these two beds, there is still potential for oyster conservation projects here. These beds could be managed for rotational harvests to provide dual benefits of supporting oyster harvests (because most will die anyway) and increased disease resistance (because this is where disease pressure drives selection fastest as long as oysters do not experience 100% mortality).*

High Priority		Medium Priority		Low Priority	

HG Harvest Guidelines
A rotational harvest pilot is recommended for the seed beds of Egg Island and Ledge which are marginal because of high disease pressure. Each (pilot) bed would be subdivided into a larger harvest section and a smaller disease resistance promotion section, which could be augmented with shell cleaning, shell planting, or seeding with disease resistant seed. The smaller set side area would be designated for no harvest for 1 to 2.5 years to allow for natural selection. After that time period, harvest would be allowed again. Disease resistance monitoring is essential to deduce success.

DR Promote disease resistance
The oyster beds identified in this area are within the medium to high mortality areas. Any activities which enhance oysters using disease resistant stocks in these zones should contribute to disease resistance promotion. See harvest guidelines for an example project.

DS Designed Shellfish Reef:
Shallow marginal areas could be potential sites for reef creation or enhancement of existing shellfish, while also furnishing additional ecological services.

LS Living Shoreline – Subtidal Breakwater
Shallow marginal areas that are nearshore represent key places to install pilot 000 oyster breakwaters, possibly in conjunction with other tactics as hybrid living shorelines.

SP Shell planting: Shell planting is recommended on Egg Island, which is a marginal area.

SM Special Management Areas:
Marginal areas in tributaries or in waters that are too shallow for oyster boats to access could become special management areas on a rotating basis (green stars on Figure 4). Many of these locations are in high productivity areas that are also closed or provisional waters for direct market harvest. Establishment of special shellfish management areas will need to balance the considerations of industry, state shellfish sanitation personnel, and the viability of oysters themselves. We also recommend that efforts be made to find the sources of shellfish closures and to have water quality remediated directly.

G Gardening
Oyster gardening represents a tactic to be used in some tributaries if state shellfish sanitation concerns can be addressed, possibly following examples from other states. Oyster gardening might become possible in DE before NJ, but until the conflicts between shellfish sanitation policies and ecological restoration goals are resolve this tactic will remain medium to low viability.

HS Hatchery, Seed Production, Population Augmentation
This tactic is a low priority as long as collection of natural spat and cultivation is effective and less expensive.

AI Intensive Aquaculture
Some local low salinity areas in the creeks might be used for seed growth areas so that diseases could be avoided. until the oysters reach a size that could be transplanted to leased areas.

AE Extensive Aquaculture:
Some shallow areas may benefit from extensive aquaculture, but this should be determined by the market.

Table 5.8: Recommended tactics for oysters in Area 2 - Marginal Areas

<u>Tributary oysters,</u> highlighted as green lines in Area 2, provide additional opportunities for conservation or restoration projects.Because fFreshwater input lowers the salinity in tributaries, disease is generally lower there, too. Oysters in the tributaries are not part of the harvested seed beds or leased beds, and in NJ many of these tributaries are within prohibited or special restricted areas. As climate change causes warmer water temperature and saltier conditions, oysters may find increasing refuge in tributaries leading to habitat expansion possibilities.

Marine Bivalve Priority Area 3: Hybrid Tactic Zones

Hybrid tactics provide opportunities to enhance shellfish using two or more conservation strategies, possibly leading to synergistic outcomes. For example, mussel-based living shorelines (intertidal, low energy) might be paired with oyster-based breakwaters (subtidal, moderate energy) to collectively reduce wave energy and enhance ecological value as a hybrid living shoreline. Similarly, oyster breakwaters near creek mouths might enhance available oyster seed stock (by augmenting larvae) for beds in the tributaries, or vice versa. Red stars in Figure 5.33 represent areas potentially suitable for living shorelines with oyster breakwaters, though many other areas may be suitable for hybrid tactics. Green lines show locations where potential tributary oyster reefs overlap with nearby breakwater/living shoreline hybrids. All of these strategies have the potential to improve nearshore oyster reefs. The salt marshes shown in yellow are also key areas for conservation, incorporating another component into the hybrid model.

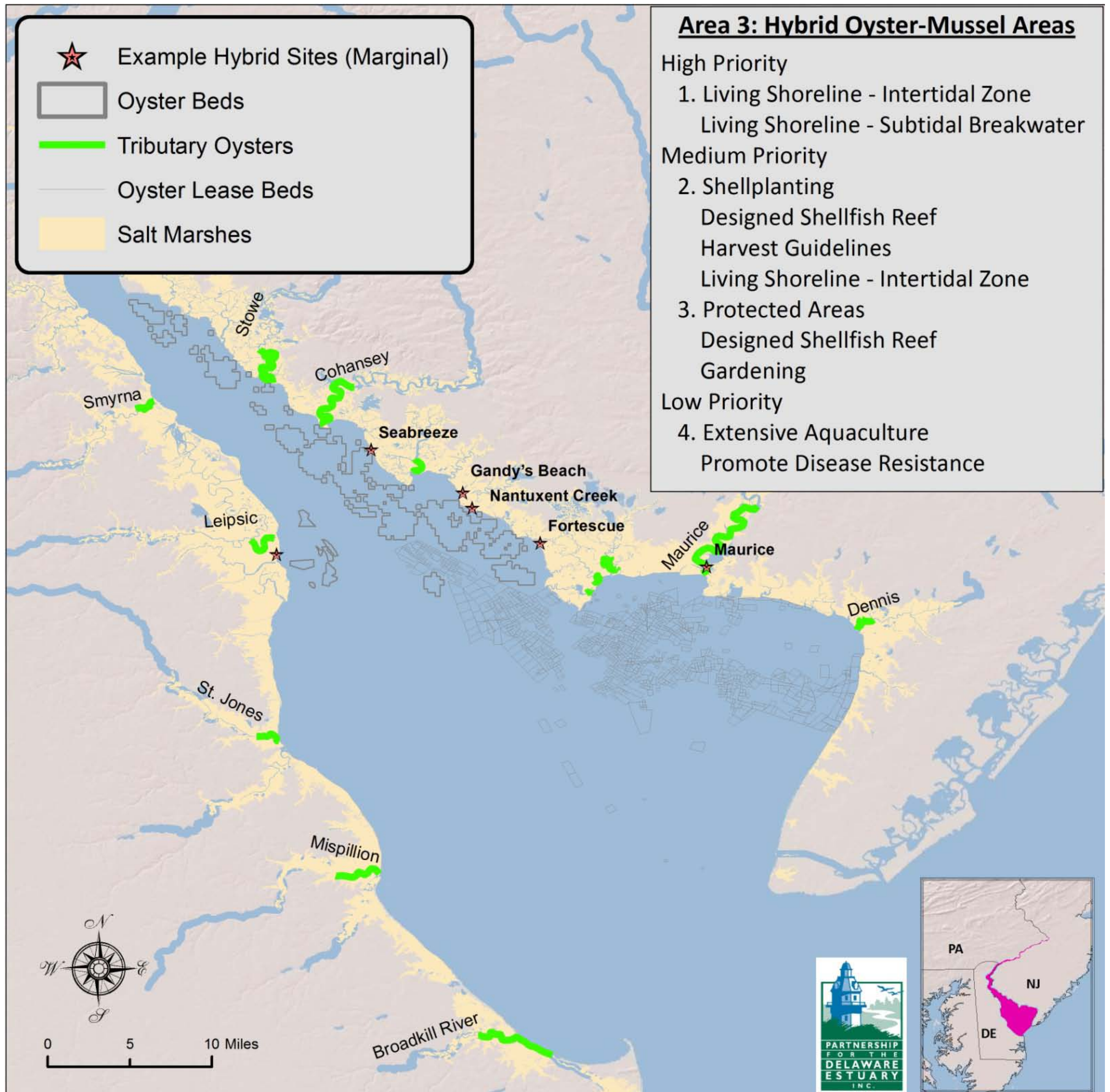


Figure 5.33. Area 3: Locations of potential hybrid tactic areas incoporating living shorelines, oyster breakwaters, and tributary oyster beds

High Priority		Medium Priority		Low Priority	

Table 5.9a. High priority – Design and implement a pilot hybrid living shoreline along the bay shore, and then expand if successful.

LSI Living Shoreline – Intertidal Zone
The red stars indicate areas which are recommended for mussel-based living shoreline tactics along salt marshes.

LSB Living Shoreline – Subtidal Breakwater
These areas are recommended for subtidal breakwater structures using oysters. Structures such as gabions can be used to contain oyster shell so that they are not readily harvested, possibly addressing shellfish sanitation concerns.

Table 5.9b. Medium Priority – Design and implement a pilot project on main seed beds that combines four conservation strategies.

SP Shell Planting
Shell planting could be employed to boost the oyster beds in a marginal area.

DS Designed Shellfish Reef
Construct a shellfish reef in the same marginal area.

HG Harvest Guidelines
See Table 5 for a full description of this strategy. Rotate harvests across pilot sites in different years, and monitor and compare oyster population success and disease resistance between harvested and unharvested sections of the project site.

LSI Living Shoreline – Intertidal Zone
The red stars indicate areas which are recommended for living shoreline tactics adjacent to salt marshes.

Table 5.9c. Medium priority - Design and implement a pilot project to enhance nearshore oysters in a shallow, marginal place using three conservation strategies.

SM Special Management Area
Marginal areas that are included in the project would be specially managed under the area management plan, providing ample protection (see Table 5 for more information).

DS Designed Shellfish Reef
The marginal oyster population at the pilot site would be augmented with reef creation tactics.

G Gardening
Oyster plots at the marginal pilot site could be installed and tended using oyster gardening concepts (see Table 5) contingent on addressing shellfish sanitation concerns.

Table 5.9d. Low priority – design and implement a pilot project to produce disease resistant stocks and outplant them, thereby using two conservation strategies together.

AI Intensive Aquaculture
Intensive aquaculture could be used to produce animals from hatchery stock, to provide enough oysters (or ribbed mussels) for outplanting (see Table 5).

DR Promote Disease Resistance
Outplant disease resistant stocks into medium to high mortality disease zones (red stars on map) to enhance disease resistance build-up in the population at the pilot site. More scientific study and discussion is warranted before implementation of this tactic. Tributary oysters might represent an ideal marginal area for outplanting disease-tolerant strains of oysters because oysters in those places might develop their own resistance slowly.

Table 5.9. Recommended tactics for Area 3 - Oyster and Mussel Hybrid Areas

Marine Bivalve Priority Area 4: Climate Change Area Targets for Future Planning

Increasing sea levels and channel deepening are likely to increase the volume of the tidal estuary, thereby allowing more seawater to move farther up Delaware Bay. Combined with increasing demands for freshwater from aquifers and the Delaware River, the Delaware Bay is expected to become saltier (Kraeuter and Kreeger 2010). Since oyster diseases are more prevalent in saltier conditions, future oyster populations will likely expand up-bay, whereas down-bay populations will be reduced due to increased disease mortality. The mortality areas will shift north and may already be changing (Kraeuter and Kreeger 2010). The current low mortality beds in the upper bay may become the new high productivity beds of the future. We therefore recommend focusing more scientific research and long-term sustainability planning on the low and very low mortality beds, which include Hope Creek, Fishing Creek, and Liston Range. New bed creation should therefore carefully consider climate change combined with expected watershed change as areas further up bay from the current seed beds become higher priorities for area management of oyster stocks. Potential oyster bed locations have been identified using acoustic data from DNREC bathymetric mapping. From these scans, two areas have been identified which might have suitable bottom, located north of current upper beds on either side of the C&D canal (Figure 5.34). Prioritizing the upper beds for protection, careful management, and possibly establishing new beds could help oyster populations to adapt to changing climate (Kraeuter and Kreeger 2010).

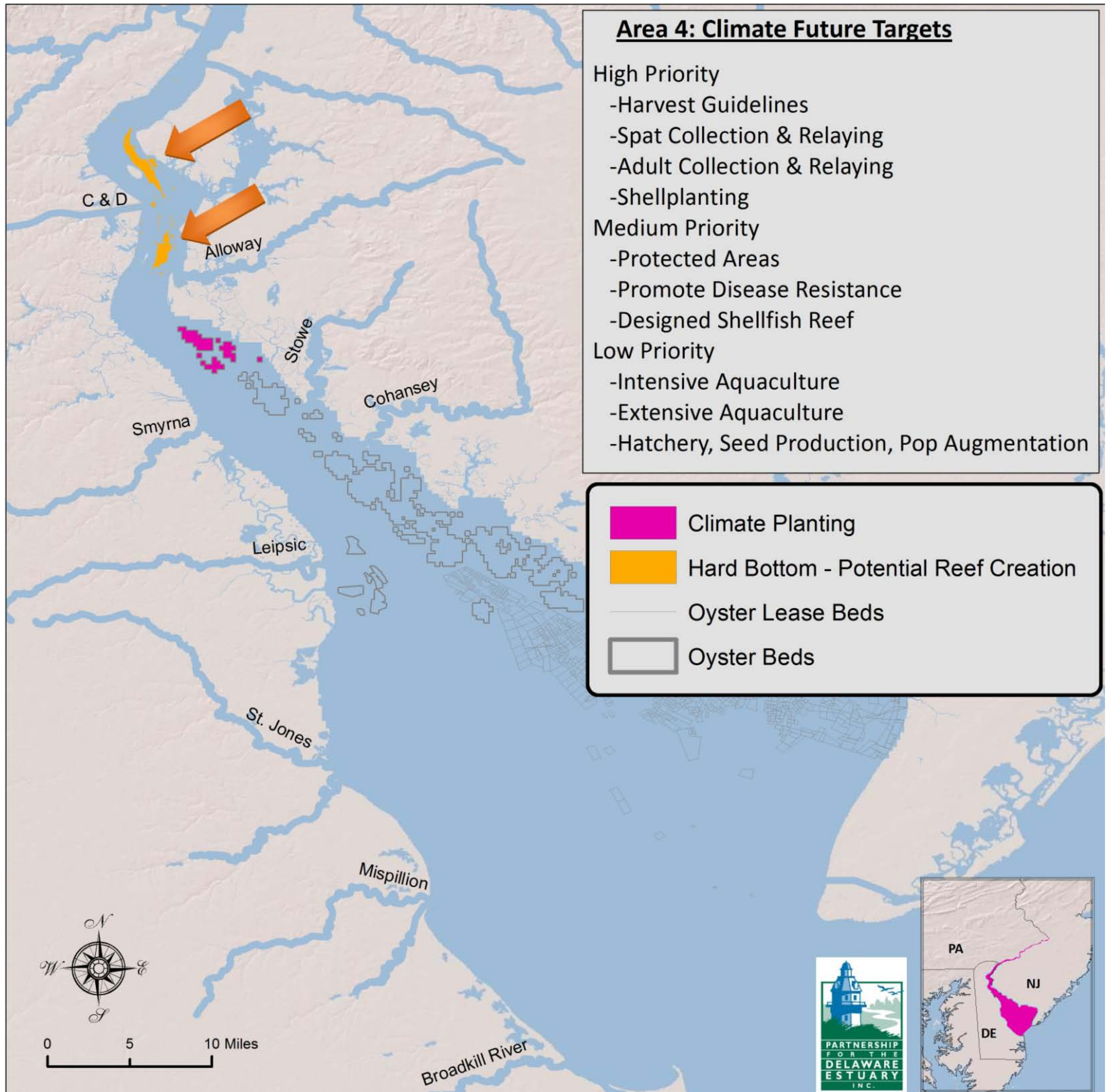


Figure 5.34. Area 4: Climate change targets for future oyster enhancement on extant upper beds, and potential areas for oyster bed creation

High Priority		Medium Priority		Low Priority	

HG **Harvest Guidelines**
The very low mortality beds are within special restricted zones, so no direct harvest for market is allowed. However, oysters are moved from these beds to the more southern beds so that they can be harvested later. It is imperative that these upper beds be studied and monitored to deduce basic population dynamics and biology so that area management and climate planning are strategic.

SR **Spat Collection & Relaying**
In the future, spatted shell might be placed on the very low mortality beds to augment naturally low recruitment and replace removed shell.

AR **Adult Collection & Relaying**
Currently a limited number of adult oysters are removed each year from the very low mortality beds to augment the high productivity beds in the mid-bay region. If monitoring and research indicate that oyster or shell abundance becomes depleted due to this practice, then the reverse could be considered whereby adults could be collected and relayed to the upper beds from high mortality areas or spat on shell from Cape Shore. Relaying is expensive and this tactic would need to be justified and funded.

SP **Shell Planting** (Future)
Since oysters grow slowly in the low and very low mortality areas, shell accumulation will curtail enhancement without shell plant augmentation. However, this approach would only be desirable if the shell had spat (e.g., from Cape Shore). Currently, natural recruitment up-bay is too sporadic to waste valuable shell resources without a better chance of success, but this could be an option for the future if recruitment dynamics change.

SM **Special Management Areas**
If new beds are created in the areas surrounding the C&D canal, these areas could be set aside for special investigations. Special area management of the newly developing or created beds may be desirable if they become more productive. Basic monitoring of environmental conditions and food availability should be undertaken before SMAs are adopted. Possibly, experimental lots of oysters could be placed in prospective areas for new bed creation and set aside on a 2-5 year rotation to confirm sustainability therein.

DR **Promote Disease Resistance**
If adults are relocated into Area 4 to augment beds or seed new beds, preference should be given to disease-resistant stocks, such as from the high mortality beds, thereby promoting broader integration of disease resistance across the bay.

DS **Designed Shellfish Reef**
The areas surrounding the C&D canal (Figure 6) are recommended for eventual new reef creation where the bottom substrate is already firm. This should be undertaken only when surveys show that conditions are conducive to establishment of oysters, and is more of a future strategy priority.

AI **Intensive Aquaculture:** See Table 5.8 for a description.

AE **Extensive Aquaculture:** See Table 5.8 for a description.

HS **Hatchery, Seed Production, Population Augmentation:** See Table 5.7 for a description

Table 5.10. Recommended tactics for Area 4 – Climate Change Target Areas

Marine Bivalve Priority Area 5: Recommended Ribbed Mussels Enhancement Areas with Tactics

All salt marshes in the Delaware Bay, the habitat of marsh mussels, have been identified as conservation priorities (Figure 5.35). By winter 2012, the Partnership for the Delaware Estuary will be releasing an inventory of living shoreline priority areas, which targets salt marsh and marsh mussel habitat. This inventory should be a useful tool for further refining ribbed mussel priority areas for direct enhancement. In addition, more ribbed mussel survey data and ecosystem services studies are needed to better prioritize specific areas for ribbed mussel enhancement in the future. Priority areas for ribbed mussels include wetland edges (where ribbed mussels can achieve greatest population biomass) and tributary watersheds in need of water quality improvements as a result of nutrient loadings, pathogens, and suspended solids. In addition, shoreline stabilization tactics using ribbed mussels or other tactics such as construction of oyster breakwaters should be prioritized to address increasing erosion energies and fetch and thereby preserve larger tracts of marsh, or protect crucial infrastructure and coastal communities. PDE is also collaborating with Rutgers to prepare a Practitioner's Guide to mussel-based living shorelines in the Delaware Estuary, expected in June 2011.

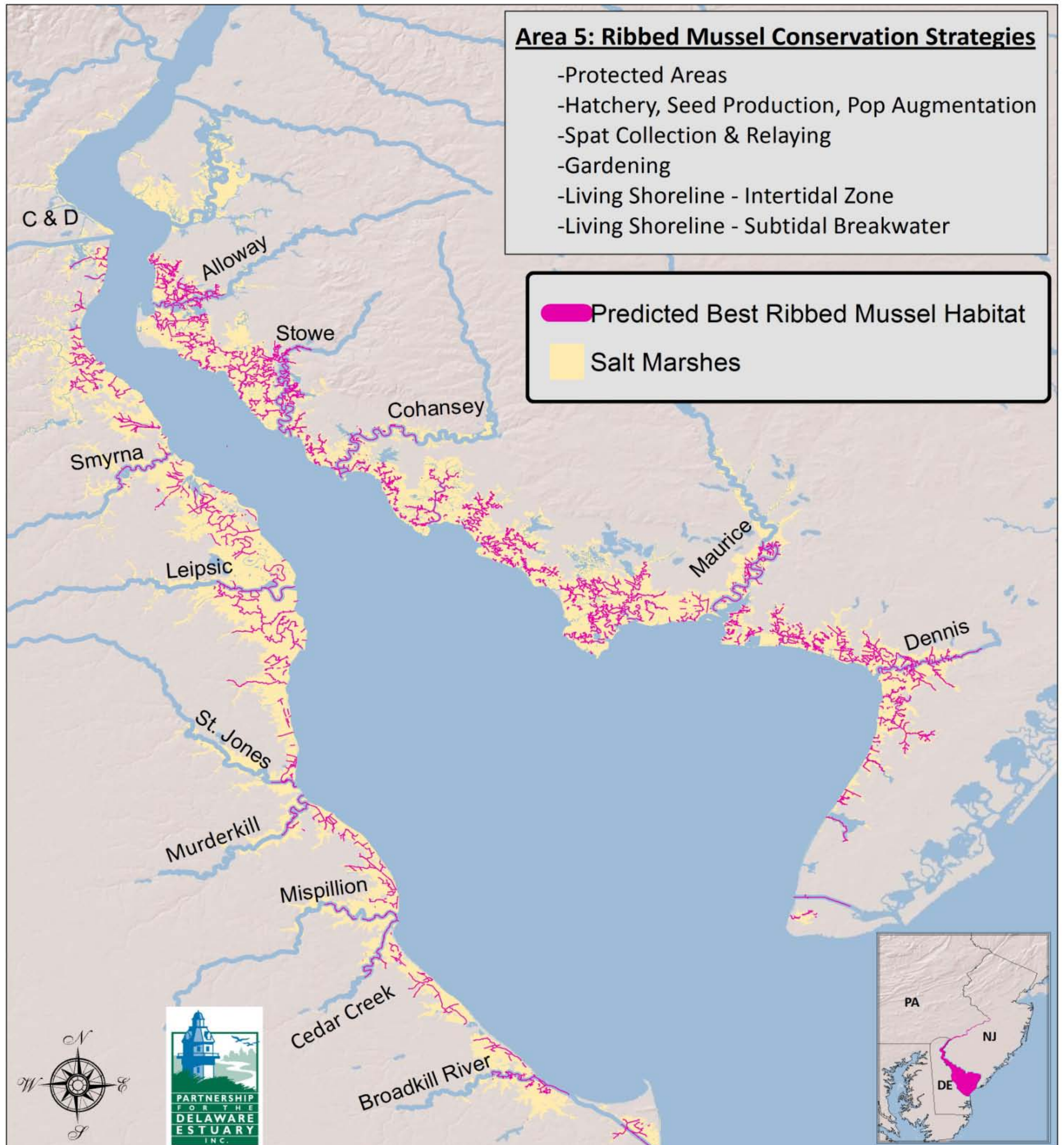


Figure 5.35. Area 5: Ribbed mussels live throughout salt marshes but are most dense along intertidal creeks and edges, which are shown here as their best habitat.

SM	**Special Management Areas** Ribbed mussels live in salt marshes, which merit their own protection for many reasons. More must be done to stem the loss of these tidal wetlands.
HS	**Hatchery, Seed Production, Population Augmentation** Spawning ribbed mussels in a laboratory has been accomplished, however, funding to develop large-scale methods that can be used for restoration and enhancement of ribbed mussel populations is needed. Such methods could grow seed mussels and plant them along salt marshes to stabilize edge erosion. Mussel seed can also be furnished to shellfish gardeners.
SR	**Spat Collection & Relaying** In salt marshes, structures might be positioned to catch ribbed mussel spat for use in restoration projects. Little is known about factors that govern ribbed mussel recruitment, which appears spatially variable. More research is needed to identify areas where mussel spat can be reliably collected and to develop spat collection methods. Natural spat collection could eventually be less expensive than hatchery propagation. Relay techniques also need R&D.
G	**Gardening** The same principles of oyster gardening could easily be applied to ribbed mussels, minus the shellfish sanitation concerns because ribbed mussels are not a commercial species. Mussel gardening would provide an educational activity and could help to raise mussels for restoration purposes and water quality improvement, potentially also benefitting oysters in impaired waters. Research is needed to determine if there is an optimal size for planting mussels, and mussel gardening could provide cost-effective research opportunities.
LS	**Living Shoreline – Intertidal Zone** Living Shorelines incorporating ribbed mussels is a new restoration tactic that appears effective at helping to stem erosion in low to moderate energy areas along salt marshes. The approach takes advantage of the stabilizing benefits of mussel byssal threads and their mutualism with *Spartina* plants. This restoration boosts populations of ribbed mussels, while also providing other ecological benefits.
LS	**Living Shoreline – Subtidal Breakwater** Subtidal (oyster) breakwaters indirectly protect ribbed mussel habitat by reducing wave energy forces, and protecting against marsh erosion. When used together with intertidal living shorelines, this tactic may be effective at collectively boosting shellfish habitat for several species.

Table 5.11. Recommended tactics for Area 5 to improve ribbed mussels in salt marshes that fringe Delaware Bay

LITERATURE CITED

Albert, R. C. 1988. The Historical Context of Water Quality Management for the Delaware Estuary. Estuaries 11:99-107.

Atlantic States Marine Fisheries Commission (ASMFC). 2007. Stock assessment of American shad, Stock Assessment Report Number 07-01. Washington, D.C., USA.

ASMFC. 2006. Terms of Reference and Advisory Report to the American Eel stock assessment peer review. ASMFC Stock Assessment Report 06-01. Washington, DC, USA.

Barrier Analysis Tool (Version 1.0) [Software]. 2010. The Nature Conservancy and the Northeast Association of Fish and Wildlife Agencies. Software Developer: Duncan Hornby.

Beck, M., Brumbaugh, R., Airoldi, L., Carranza, A., Coen, L., Crawford, C., et al. 2009. *Shellfish Reefs at Risk: A Global Analysis of Problems and Solutions.* Arlington, VA: The Nature Conservancy.

Basnyat, P., L. D. Teeter, K. M. Flynn, and B. G. Lockaby. 1999. Relationships between landscape characteristics and nonpoint source pollution inputs to coastal estuaries. Environmental Management 23: 539–549.

Boesch, D. F. and R. E. Turner. 1984. Dependence of fishery species on salt marshes: the role of food and refuge. Estuaries. 7(4): 460-468.

Bott, T. L., J. T. Brock, C. S. Dunn, R. J. Naiman, R. W. Ovink, and R. C. Petersen. 1985. Benthic community metabolism in four temperate stream systems: An inter-biome comparison and evaluation of the river continuum concept. Hydrobiologia 123:3-45.

Brauning, D.W. 1992. Atlas of Breeding Birds in Pennsylvania. Pittsburgh: University of Pittsburgh Press.

Burns, R. M. and B. H. Honkala. 1990. Silvics of North America, Volumes I (Conifers) and II (Hardwoods). Agriculture Handbook 654. U.S. Department of Agriculture, Forest Service. Washington, D.C.

Calhoun, A. J and P. G. deMaynadier. 2008. Science and Conservation of Vernal Pools in Northeastern North America. New York: CRC Press.

Chittenden, M. E. 1974. Trends in the abundance of American shad Alosa sapidissima in the Delaware River Basin. Chesapeake Science 15:96–103.

Ciruna, K. and D. Braun. 2005. Chapter 2: Freshwater Fundamentals: Watersheds, Freshwater Ecosystems, and Freshwater Biodiversity. Pp. 11-36 in A Practitioner's Guide to Freshwater Biodiversity Conservation, eds. N. Silk and K. Ciruna. Washington: Island Press.

Climate Change Science Program (CCSP). 2009. Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [James G. Titus (Coordinating Lead Author), K. Eric Anderson, Donald R. Cahoon, Dean B. Gesch, Stephen K. Gill, Benjamin T. Gutierrez, E. Robert Thieler, and S. Jeffress Williams (Lead Authors)]. U.S. Environmental Protection Agency, Washington D.C., USA, 320 pp.

Coen, L., and R. Grizzle. 2007. The importance of habitat created by molluscan shellfish to managed species along the Atlantic Coast of the United Coast. In J. Thomas, & J. Nygard, *Habitat Management Series 8* (p. 108). Washington, DC: Atlantic States Marine Fishery Commission.

Coen, L. and K. Walters. 2011. Ribbed Mussels, *Geukensia demissa*. North Carolina Department of Natural Resources. http://www.dnr.sc.gov/cwcs/pdf/Ribbedmussel%20.pdf (accessed Jan 25, 2011).

Cole, J. C., P. A. Townsend, and K. N. Eshleman. 2008. Predicting flow and temperature regimes at three *Alasmidona heterodon* locations in the Delaware River. Technical Report NPS/NER/NRTR-2008/109. National Park Service. Philadelphia, PA.

Committee on Riparian Zone Functioning and Strategies for Management. 2002. Riparian areas: Functions and strategies for management. Water Science and Technology Board, Board on Environmental Studies and Toxicology, Division of Earth and Life Studies, National Research Council. National Academies Press. Washington, D.C.

Conant, R. and J. T. Collins. 1998. A Field Guide to Reptiles and Amphibians of Eastern and Central North America. 3rd ed. New York: Houghton Mifflin Company.

Connecticut Department of Environmental Protection (CTDEP). 2003. A Field Guide to the Freshwater Mussels of Connecticut. CTDEP, Bureau of Natural Resources, Wildlife Division. Hartford, CT.

Cooper, E.L. 1983. Fishes of Pennsylvania and the Northeastern United States. University Park: Pennsylvania State University Press.

Cowardin, L. M., V. Carter, F. C. Golet, and E. T. LaRoe. 1979. Classification of wetlands and deepwater habitats of the United States. U.S. Fish and Wildlife Service. Washington, D.C.

Cuffney, T. F., Brightbill, R. A., May, J. T., and Waite, I. R. 2010. Responses of benthic macroinvertebrates to environmental changes associated with urbanization in nine metropolitan areas. Ecological

Applications 20(5): 1384–1401.

Dahl, T. E. 2006. Status and trends of wetlands in the conterminous United States, 1998 to 2004. U.S. Department of the Interior; Fish and Wildlife Service, Washington, D.C.

Davis, A. F. 1993. Rare wetland plants and their habitats in Pennsylvania. Proceedings of the Academy of Natural Sciences of Philadelphia 114: 254-262.

Delaware River Basin Commission (DRBC). 2008. Delaware River State of the Basin Report

DRBC. 2011a. http://www.state.nj.us/drbc/edweb/baldeagle.htm. Accessed April 8, 2011.

DRBC. 2011b. Special Protection Waters – Keeping the Clean Waters Clean. http://www.state.nj.us/drbc/spw.htm. Accessed May 19, 2011

Delaware Basin Fish & Wildlife Management Cooperative. 1982. A Fishery Management Plan for the American Shad (*Alosa sapidissima*) in the Delaware River Basin. 26pp.

Denslinger, T. L., W. Gast, J. Hauenstein, D. Heicher, J. Henriksen, D. Jackson, G. Lazorchick, J. McSparran, T. Stoe, and L. Young. 1998. Instream flow studies: Pennsylvania and Maryland. Susquehanna River Basin Commission. Harrisburg, PA.

Donnelly, J. P. and M. D. Bertness. 2001. Rapid shoreward encroachment of salt marsh cordgrass in response to accelerated sea-level rise. Proceedings of the National Academy of Sciences of the United States of America 98: 14218-14223.

Durlin, R.R. and W.P. Schaffstall, 1997. Water Resources Data for Pennsylvania, Water Year 1997, Volume 1,Delaware River Basin: U.S. Geological Survey Water-Data Report PA-97-1.

Edgar, G. J., G. R. Russ, and R. C. Babcock. 2007. Marine protected areas. In: Marine Ecology. South Melbourne, VIC, Australia: Oxford University Press.

Eichelberger, B. A., G. S. Podniesinski, and T.F. Davis. 2009. Assessment of high priority floodplain plant communities along the Delaware River. Pennsylvania Natural Heritage Program. Middletown, PA.

Ford, S., & Bushek, D. (in prep). Development of resistance to an introduced pathogen by a native host. *Target journal: J. Marine Research (should be submitted shortly)* Environmental Law Institute. 2010. Delaware Wetland Program Review. Environmental Law Institute. Washington, D.C.

Faber-Langendoen, D., G. Kudray, C. Nordman, L. Sneddon, L. Vance, E. Byers, J. Rocchio, S. Gawler, G. Kittel, S. Menard, P. Comer, E. Muldavin, M. Schafale, T. Foti, C. Josse, and J. Christy. 2008.

Ecological Performance Standards for Wetland Mitigation: An Approach Based on Ecological Integrity Assessments. NatureServe. Arlington, VA.

Fanok, S. F., B. A. Eichelberger, A. F. Davis, and G. S. Podniesinski. 2009. Riparian plant communities of the Delaware River: A framework for identifying and conserving representative riparian communities of the Delaware River from Hancock New York to the Delaware Water Gap. Harrisburg, PA.

Fanok, S. 2000. A groundwater chemistry and flow system assessment for the Mt. Bethel Fens. The Nature Conservancy. Harrisburg, PA.

Fausch, K. D., C. E. Torgensen, C. V. Baxter, and H. W. Li. 2002. Landscapes to riverscapes: Bridging the gap between research and conservation of stream fishes. BioScience 52:483-498.

Field, R. T. and K. R. Philipp. 2000. Vegetation changes in the freshwater tidal marsh of the Delaware Estuary. Wetlands Ecology and Management 8: 79-88.

Fike, J. 1999. Terrestrial and palustrine plant communities of Pennsylvania. A publication of the Pennsylvania Department of Natural Resources, Bureau of Forestry. Harrisburg, Pennsylvania.

Fischer, R. A., and J. C. Fischenich. 2000. Design recommendations for riparian corridors and vegetated buffer strips. EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-24), U.S. Army Engineer Research and Development Center. Vicksburg, MS. www.wes.army.mil/el/emrrp

Fitzgerald, D. M., M. S. Fenster, B. A. Argow, and I. V. Buynevich. 2008. Coastal impacts due to sea level rise. Annual Review of Earth and Planetary Sciences 36: 601-647.

Fitzhugh, T. W. and R. M. Vogel. 2010. The impact of dams on flood flows in the United States. River Research Applications DOI: 10.1002/rra.1417.

Ford, S. E. 1997. History and Present Status of Molluscan Shellfisheries from Barnegat Bay to Delaware Bay. In The History, Present Condition, and Future of the Molluscan Fisheries of North and Central America and Europe, Vol. 1, Atlantic and Gulf Coasts, by L.M. Clyde et al. (eds), 119-140. NOAA Technical Report NMFS 127, A Technical Report of the Fisheries Bulletin.

Fox, D. and M. Fisher. 2010. Personal communication.

Gillanders, B. M. and M. J. Kingsford. 2002. Impact of changes in flow of freshwater on estuarine and open coastal habitats and the associated organisms. Oceanography and Marine Biology 40: 233–309.

Gomi, T., R. C. Sidle, and J. S. Richardson. 2002. Understanding processes and downstream linkages of headwater systems. BioScience 52:10.

Grabarkiewicz, J. and W. Davis. 2008. An Introduction to Freshwater Mussels as Biological Indicators (Including Accounts of Interior Basin, Cumberlandian and Atlantic Slope Species). EPA-260-R-08-015. U.S. Environmental Protection Agency, Office of Environment. Washington, D.C.

Greeley, J. R. 1936. A biological survey of the Delaware and Susquehanna watersheds; New York State Conservation Department 25th Annual Report. Albany, NY.

Greene, K. E., J. L. Zimmerman, R. W. Laney, and J. C. Thomas-Blate. 2009. Atlantic coast diadromous fish habitat: A review of utilization, threats, recommendations for conservation, and research needs. Atlantic States Marine Fisheries Commission Habitat Management Series #9. Washington, D.C.

Groves, C. R. 2003. Drafting a conservation blueprint: A practitioner's guide to planning for biodiversity. Washington: Island Press.

Hack J. T. and J. C. Goodlett. 1960. Geomorphology and forest ecology of a mountain region in the Central Appalachians. Washington (DC): US Geological Survey. Professional paper no. 347.

Hakala, J. P. and K. J. Hartman. 2004. Drought effect on stream morphology and brook trout (*Salvelinus fontinalis*) populations in forested headwater streams. Hydrobiologia 515:203-213.

Harding. Charles. 1999. Fish or Foul: A History of the Delaware River Basin Through the Perspective of the American Shad," *Pennsylvania History* 66:4: 506-534.

Horwitz, R.J., D. Keller, S. Moser and P. Overbeck. 2008. Neversink Shad Study, Final Report. Submitted to The Nature Conservancy, Patrick Center for Environmental Sciences. The Academy of Natural Sciences. 23pp.

Horwitz, R., P. Overbeck, D. Keller, and S. Moser. 2008. Fish inventories of Delaware Water Gap National Recreation Area and Upper Delaware Scenic and Recreational River. Academy of Natural Sciences Report No. 08-06. Prepared for U.S. Department of the Interior, National Park Service, Northeast Region. Philadelphia, PA.

Hudy, M., T. Thieling, N. Gillespie, and E. P. Smith. 2005. Distribution, status, and perturbations of brook trout within the eastern United States. Final Report Eastern Brook Trout Joint Venture.

Hulse, A. C., C. J. McCoy, and E. J. Censky. 2000. Amphibians and Reptiles of Pennsylvania and the Northeast. New York: Cornell University Press.

Hutchens, J. J., J. B. Wallace, and E. D. Romaniszyn. 2004. Role of *Podostemum ceratophyllum* in structuring benthic macroinvertebrate assemblages in a southern Appalachian river. Journal of the North American Benthological Society 23: 713-727.

Jenkins, R. E and N. M. Burkhead. 1993. Freshwater Fishes of Virginia. American Fisheries Society, Bethesda, Maryland.

Kaplan, L. A., T. L. Bott, J. K. Jackson, J. D. Newbold, and B. W. Sweeney. 2010. Protecting headwaters: The scientific basis for safeguarding stream and river ecosystems. Stroud Water Research Center. Avondale, PA.

King, R. S. and M. E. Baker. 2010. Considerations for analyzing ecological community thresholds in response to anthropogenic environmental gradients. Journal of the North American Benthological Society 29: 998–1008.

Kraeuter, J., & Kreeger, D. 2010. Appendix O: Oysters in the Delaware Bay - Climate Change. In D. Kreeger, J. Adkins, P. Cole, R. Najjar, D. Velinsky, & P. Conolly, *Climate Change in the Delaware Estuary: Three Case Studies in Vulnerability Assessment and Adaptation Planning*). Wilmington, DE: Partnership for the Delaware Estuary, Report No. 10-01: 1-117. http://delawareestuary.org/science_reports_partnership.asp

Kreeger, D., 2009. Integrated monitoring and assessment program for tidal wetlands of the Delaware Estuary, version 1.0. Prepared for U.S. Environmental Protection Agency Region III.

Kreeger, D., J. Adkins, P. Cole, R. Najjar, D. Velinsky, P. Conolly, and J. Kraeuter. 2010. Climate Change and the Delaware Estuary: Three Case Studies in Vulnerability Assessment and Adaptation Planning. Partnership for the Delaware Estuary, PDE Report No. 10-01.

Kreeger, D. P. Cole, D. Bushek, J. Kraeuter, and J. Adkins. 2011a. Marine Bivalve Shellfish: Conservation Priorities for the Delaware Estuary. Partnership for the Delaware Estuary, Report No. 11-03. On the web: http://delawareestuary.org/science_reports_partnership.asp

Kreeger, D., & Gatenby, C. 2007. From local to regional: contrasting the water processing and restoration potential of native bivalves throughout the Delaware Estuary and its watershed. Proceedings of the 2nd Delaware Estuary Science & Environmental Summit. P. Cole and D. Kreeger (Eds.) Partnership for the Delaware Estuary. Report No. 11-01. pp. 59. http://delawareestuary.org/science_reports_partnership.asp

Kreeger, D. A. Homsey, A. Padeletti and K. Strait. 2011b. Tidal Wetland Indicators for the 2011 State of the Delaware Estuary and Basin Technical Report. Proceedings of the Fourth Delaware Estuary Science and Environmental Summit. Partnership for the Delaware Estuary Report 11-01. http://www.delawareestuary.org/news_pde_science_conference.asp

Kreeger, D., & Kraeuter, J. 2010. Appendix N: Ecologically Significantly Bivalve Molluscs of the Delaware Estuary. In Climate Change and the Delaware Estuary. Wilmington, DE: Partnership for the Delaware Estuary, Report No. 10-01. http://delawareestuary.org/science_reports_partnership.asp

Lathrop, R., M. Cole, and R. Showalter. 2000. Quantifying the habitat structure and spatial pattern of New Jersey (U.S.A.) salt marshes under different management regimes. Wetlands Ecology and Management 8: 163-172.

Lellis, W. and C. S. Johnson. 2006. Propagation of two Pennsylvania endangered shiners, *Notropis bifrenatus* and *Notropis chalybaeus*, at the USGS Northern Appalachian Research Laboratory. Final Report to Pennsylvania Department of Transportation Contract No. 430643.

Leopold, L. B., M. G. Wolman, and J. P. Miller. 1964. Fluvial Processes in Geomorphology. San Francisco: CA W.H. Freeman and Company.

Letcher, B. H., K. H. Nislow, J. A. Coombs, M. J. O'Donnell, and T. L. Dubreuil. 2007. Population response to Habitat Fragmentation in a stream-dwelling brook trout population. PLOSone: 11:e1139.

May, C. 2007. Sediment and wood routing in steep headwater streams: An overview of geomorphic processes and their topographic signatures. Forest Science 53:119-130.

McGowan, Conor P., James E. Hines, James D. Nichols, James E. Lyons, David R. Smith, Kevin S. Kalasz, Lawrence J. Niles, Amanda D. Dey, Nigel A. Clark, Philip W. Atkinson, Clive D. T. Minton, and William Kendall. 2011. Demographic consequences of migratory stopover: linking red knot survival to horseshoe crab spawning abundance. Ecosphere 2: art69.

McKinney, R., M. Charpentier, and C. Wigand.2009. Assessing the wildlife habitat value of New England salt marshes: I. Model and application. Environmental Monitoring and Assessment 154: 29-40.

McPhee, J. 2002. The founding fish. New York: Farrar, Straus and Giroux.

Merritt, J.F. 1987. Guide to the Mammals of Pennsylvania. Pittsburgh: University of Pittsburgh Press.

Meyer, J. L., D. L. Strayer, J. B. Wallace, S. L. Eggert, G. S. Helfman, and N.E. Leonard. 2007. The contribution of headwater streams to biodiversity in river networks. Journal of the American Water Resources Association 43:86-103.

Meyer, J. L. and J. B. Wallace. 2001. Lost linkages and lotic ecology: Rediscovering small streams. Pages 295–317 in Press MC, Huntly NJ, Levin S, eds. Ecology: Achievement and Challenge. Oxford (United Kingdom): Blackwell Scientific.

Mitch, W. J. and J. G. Gosselink. 2000. The Value of Wetlands: Importance of Scale and Landscape Setting. Ecological Economics 35(1): 25-33.

Moberg, T., C. Apse, and M. DePhilip. 2010. Flow alteration in the Upper Delaware River Basin: a historical analysis of water supply reservoir management impacts (1954-2009). The Nature Conservancy, Harrisburg, PA.

Moore, C. M. and M. L. Sievert. 2001. Temperature-mediated characteristics of the dusky salamander (*Desmognathus fuscus*) of southern Appalachia. Journal of Thermal Biology 26:547-554.

Munch, S. 1993. Distribution and condition of populations of *Podostemum ceratophyllum* (riverweed) in Pennsylvania. Journal of the Pennsylvania Academy of Science 67(2): 65-72.

Naiman, R. J. and H. Décamps. 1997. The ecology of interfaces: Riparian zones. Annual Review of Ecology and Systematics 28:621-658.

National Land Cover Database. 2001. http://www.mrlc.gov/nlcd.php

Nedeau, E. J., M. A. McCollough, and B. I. Swarts. 2000 The Freshwater Mussels of Maine. Maine Department of Inland Fisheries and Wildlife. Augusta, ME.

Neubauer, S. C., I. C. Anderson, J.A. Constantine, and S. A. Kuehl. 2002. Sediment deposition and accretion in a mid-Atlantic (U.S.A.) tidal freshwater marsh. Estuarine, Coastal, and Shelf Science 54: 713-727.

NJ DEP. New Jersey Department of Environmental Protection. 2005. Locations of anadromous American shad and river herring during their spawning period in New Jersey's freshwaters including known migratory impediments and fish ladders. Division of Fish and Wildlife Bureau of Freshwater Fisheries Southern Regional Office Sicklerville, NJ. 13 pp.

New York Department of Environmental Conservation (NYDEC). 2011. Ironcolor shiner (*Notropis chalybaeus*) factsheet. http://www.dec.ny.gov/animals/26037.html. Accessed April 2011.

Nixon, S.W. 1980. Between coastal marshes and coastal water—a review of twenty years of speculation and research in the role of salt marshes in estuarine productivity and water chemistry. pp. 437-525 in P. Hamilton and K.B. MacDonald, eds. Wetland processes with emphasis on modeling. Plenum Press, New York, NY. USA.

National Oceanic and Atmospheric Administration (NOAA). 2011. The Delaware Project, NOAA Trust Resources, Delaware River Species Life History. http://mapping2.orr.noaa.gov/portal/Delaware/lifehistory.html. Accessed April 2011.

NOAA. 2001. Wetlands and fish: Catch the link. National Marine Fisheries Service, Office of Habitat Conservation, Silver Spring, MD. 48 pp.

O'Connell, T. J., R. P. Brooks, R. S. Mulvihill, T. L. Master, and S. E. Laubscher. 2003. Using bioindicators to develop a calibrated index of regional ecological integrity for forested headwater ecosystems. Final Report to U.S. Environmental Protection Agency, STAR Grants Program. Report No. 2003-01. University Park, PA: Penn State Cooperative Wetlands Center, Pennsylvania State University; 247pp.

Odum, W. E. 1988. Comparative ecology of tidal freshwater and salt marshes. Annual Review of Ecology, Evolution, and Systematics 19: 147-176.

Olivero, A. and M. G. Anderson. 2008. Northeastern Habitat Classification System. The Nature Conservancy, Boston, MA.

Opperman, J. J., R. Luster, B. A. McKenny, M. Roberts, and A. W. Meadows. 2010. Ecologically functional floodplains: Connectivity, flow regime, and scale. Journal of the American Water Resources Association 46: 211-226.

Partnership for the Delaware Estuary (PDE). 2007. Delaware Estuary Oyster Restoration Brochure. Wilmington, DE: Partnership for the Delaware Estuary.

Pennsylvania Environmental Council (PEC) with Support of Urban Water Front Case Study Workgroup. 2009. Philadelphia North Delaware River Greenway Ecological Assessment and Prioritization Report. Final Report for Pennsylvania Coastal Zone Management Program, Grant Number 2007PS.05--Includes Additional Assessment Work Underway for Partnership for Delaware Estuary's Blue Print for Delaware Estuary Urban Water Front Case Study. 38pp.

Pennsylvania Fish and Boat Commission (PFBC). 2011. Draft Delaware River Management Plan: A management plan focusing on the large river habitats of the West Branch Delaware river and non-tidal reach of the Delaware River of Pennsylvania. Pennsylvania Fish and Boat Commission, Bureau of Fisheries, Division of Fisheries Management. Harrisburg, PA.

Pennsylvania Game Commission (PGC) and PFBC. 2005. Pennsylvania Comprehensive Wildlife Conservation Strategy, Version 1.0. Harrisburg, PA.

Pennsylvania Natural Heritage Program (PNHP). 2010. Bridled Shiner (*Notropis bifrenatus*) factsheet 11313. http://www.naturalheritage.state.pa.us/factsheets/11313.pdf. Accessed April 29, 2011.

Pennsylvania Natural Heritage Program (PNHP). 2010b. Bog Turtle (*Glyptemys muhlenbergii*) factsheet 11313. http://www.naturalheritage.state.pa.us/factsheets/11313.pdf. Accessed April 29, 2011.

Pennsylvania Wildlife Action Plan. 2005. American Shad Species Account by M.L. Hendricks 2 pp.

Peterjohn, W. T. and D. L. Correll. 1984. Nutrient dynamics in an agricultural watershed: Observations on the role of riparian forest. Ecology 65:1466-1475.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K .L. Prestegaard, B. Richter, R. Sparks, and J. Stromberg. 1997. The natural flow regime: a new paradigm for riverine conservation and restoration. BioScience 47:769-784.

Poff, N. L. and D. D. Hart. 2002. How dams vary and why it matters for the emerging science of dam removal. BioScience 52: 659-668.

Powell, E. N., K. Ashton-Alcox, and D. Bushek. 2011. Report of the 2011 Stock Assessment Workshop (13th SAW) for the New Jersey Delaware Bay Oyster Beds. HSRL Report 155.

The Reef Ball Foundation. 2011. Designed Artificial Reefs. http://www.reefball.org/. Accessed Jan 10, 2011.

Richards, T. M. and R.A.Seigel. 2009. Habitat use of northern map turtles (*Graptemys geographica*) in an altered system, the Susquehanna River, Maryland (USA)- Poster Presentation at 2009 ESA Conference.

Rocco, G. L. and R. P. Brooks. 2000. Abundance and distribution of Stream Plothodontid Salamander Assemblage in 14 Ecologically Dissimilar Watershed in the Pennsylvania Central Appalachians. Report No. 2000-4. Penn State Cooperative Wetlands Center. University Park, PA.

Rodriguez, W., P. V. August, Y. Wang, J. F. Paul, A. Gold, and N. Rubinstein. 2006. Empirical relationships between land use/cover and estuarine condition in the Northeastern United States. Landscape Ecology 22: 403-417.

Ross, R. M., L. A. Redell, R. M. Bennett, and J. A.Young. 2004. Mesohabitat use of threatened hemlock forests by breeding birds of the Delaware river basin in northeastern United States. Natural Areas Journal 24:307–315.

Sabaj, M. H., E. G. Maurakis, and W. S. Woolcott. 2000. Spawning Behaviors in the bluehead chub, *Nocomis leptocephalus*, river chub, *N. micropogon* and central stoneroller, *Campostoma anomalum*. The American Midland Naturalist 144: 187-201.

Santoro, E. D. and R. L. Limbeck. 2008. Nutrient Criteria Strategy for the Tidal And Non-Tidal Delaware River , April 25, 2008 Version. Delaware River Basin Commission. West Trenton, NJ.

Sartor, J. F. 2005. Flood water retention by riverine and terrestrial forests. American Society of Civil Engineers Conference Proceedings 178: 81.

Saunders, D. L., J. J. Meeuwig, and A. C. J. Vincent. 2002. Freshwater protected areas: Strategies for conservation. Conservation Biology 16(1):30-41.

Schumm, S. A. 1977. The Fluvial System. New York: John Wiley and Sons.

Schumm, S.A. and R. W. Lichty. 1965. Time, space and causality in geomorphology. American Journal of Science 263:110–119.

Shreve, R. L. 1969. Stream lengths and basin areas in topologically random channel networks. Journal of Geology 77:397-414.

Sidle, R. C, Y. Tsuboyama, S. Noguchi, I. Hosoda, M. Fujieda, and T. Shimizu. 2000. Streamflow generation in steep headwaters: A linked hydro-geomorphic paradigm. Hydrological Processes 14: 369–385.

Simpson , P.C. and D.A. Fox. 2007. Atlantic sturgeon in the Delaware River: contemporary population status and identification spawning areas Completion Report: Award NA05NMF4051093. http://www.nero.noaa.gov/StateFedOff/grantfactsheets/DE/FINAL%20REPORTS/FINAL%20NA05NMF4051093.pdf Accessed: 18 May 2011.

Simpson, R. L., R. E. Good, M. A. Leck, and D. F. Whigham. 1983. The ecology of freshwater tidal wetlands. BioScience 33(4): 255-259.

Sloto, R. and D. Buxton. 2007. Estimated ground-water availability in the Delaware River Basin, 1997-2000. Scientific Investigations Report 2006-5125-Version 1.1. U.S. Geological Survey, Reston, VA.

Smith, D. G. 1985. Recent range expansion of the freshwater mussel *Anodonta implicata* and its relationship to clupeid fish restoration in the Connecticut River system. Freshwater Invertebrate Biology 4(2): 105-108.

Smith, M. P., R. Schiff, A. Olivero, and J. G. MacBroom. 2008. The Active River Area: A conservation framework for protecting rivers and streams. The Nature Conservancy. Boston, MA.

Sowa, S. P., D .D. Diamond, R. Abbitt, G. M. Annis, T. Gordon, M. E. Morey, G. R. Sorensen, and D. True. 2004. The aquatic component of gap analysis: A Missouri prototype final report. Missouri Resource Assessment Partnership, University of Missouri. Columbia, Missouri.

Stedman, S. and T.E. Dahl. 2008. Status and Trends of Wetlands in the Coastal Watersheds of the

Eastern United States 1998 to 2004. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, and U.S. Department of the Interior, Fish and Wildlife Service. 36 pp.

Stevenson D., L. Chiarella, D. Stephan, R. Reid, K. Wilhelm, J. McCarthy and M. Pentony. 2004. Characterization of the fishing practices and marine benthic ecosystems of the northeast US shelf, and an evaluation of the potential effects of fishing on essential habitat. NOAA Technical Memorandum. NMFS NE 181. 179 pp.

Strakosh, T. R., J. L. Eitzmann, K. B. Gido, and C. S. Guy. 2005. The response of water willow *Justicia americana* to different water inundation and desiccation regimes. North American Journal of Fisheries Management 25:1476-1485.

Strayer, D. L and K. J. Jirka. 1997. The Pearly Mussels of New York State. New York State Museum Memoir 26. The New York State Education Department. Albany, NY.

Sutton, C. C., J. C. O'Herron, and R. T. Zappalorti. 1996. The Scientific Characterization of the Delaware Estuary. Delaware Estuary Program. (DRBC Project No. 321; HA File No. 93.21). 200pp. and appendices.

Sweeney, B. W., T. L. Bott, J. K. Jackson, L. A. Kaplan, J. S. Newbold, L. J. Standley, W. C. Hession, and R. J. Horwitz. 2004. Riparian deforestation, stream narrowing, and loss of stream ecosystem services. Proceedings of the National Academy of Sciences 101:14132-14137.

Tews, J., U. Brose, V. Grimm, K. Tielbörger, M. C. Wichmann, M. Schwager, and F. Jeltsch. 2004. Animal species diversity driven by habitat heterogeneity/diversity: the importance of keystone structures. Journal of Biogeography 31: 79–92.

Tiner, R. W. 1984. Wetlands of the United States: current status and recent trends. National Wetlands Inventory, U. S. Fish and Wildlife Service, Washington, D. C. 76pp.

U.S. Fish and Wildlife Service (USFWS). 2011. Swamp pink (*Helonias bullata*) factsheet. http://www.fws.gov/northeast/njfieldoffice/Endangered/swamppink.html. Accessed April 8, 2011.

USFWS. 2010. Supawna Meadows National Wildlife Refuge: Draft comprehensive conservation plan and environmental assessment. USFWS, Northeast Regional Office. Cape May, NJ .

USFWS. 1983. Northern States Bald Eagle Recovery Plan. Northern States Bald Eagle Recovery Team. Denver, CO.

U.S. Geological Survey (USGS). 2003. Contaminant exposure and potential reproductive effects on Ospreys nesting in the Delaware Bay and River, Science Brief PWRC 2003-04. Patuxent Wildlife Research Center. Laurel, MD.

U.S. National Park Service. 1997. Lower Delaware River Management Plan. Prepared in cooperation with the Lower Delaware Wild and Scenic River Study Task Force. Philadelphia, PA.

Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell, and C.E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences 37:130-7.

Valiela, I. and J. L. Bowen. 2002. Nitrogen sources to watersheds and estuaries: role of land cover mosaics and losses within watersheds. Environmental Pollution 118: 239-248.

Virginia Department of Environmental Quality (VDEQ). 2010. Virginia Oyster Gardening Guide. http://www.deq.state.va.us/coastal/gardening.html. Accessed November 11, 2010.

Vogel, R. M., J. Sieber, S. A. Archfield, M. P. Smith, C. D. Apse, and A. Huber-Lee. 2007. Relations among storage, yield, and instream flow. Water Resources Research, Vol. 43, W05403.

Ward, J. V., K. Tockner, and F. Schiemer. 1999. Biodiversity of floodplain river ecosystems: Ecotones and connectivity. Regulated Rivers: Research and Management 15:125-139.

Weishar, L., J. Teal, and R. Hinkle. 2005. Designing large-scale wetland restoration for Delaware Bay. Ecological Engineering 25: 231-239.

Wenger, S. 1999. A Review of the Scientific Literature on Riparian Buffer Width, Extent and Vegetation. Institute of Ecology, University of Georgia, Athens.

Weslager, C. A. 1944. Delaware's Buried Past. Philadelphia: University of Pennsylvania Press.

Weslager, C. A. 1972. The Delaware Indians. New Brunswick, NJ: Rutgers University Press.

Westervelt, K., E. Largay, R. Coxe, W. McAvoy, S. Perles, G. Podniesinski, L. Sneddon, and K. Strakosch Walz. 2006. Guide to the Natural Communities of the Delaware Estuary: Version 1. NatureServe, Arlington, Virginia. Partnership for the Delaware Estuary, Report #06-02. 338 pp.

Whalen, L., D. Kreeger, D. Bushek, and J. Moody. 2011. Delaware Estuary Living Shorelines Inventory: Focus on Delaware Coast Suitability. PDE Report Number 11-01.

Wipfli, M. S., J. S. Richardson, and R. J. Naiman. 2007. Ecological linkages between headwaters and downstream ecosystems: Transport of organic matter, invertebrates, and wood down headwater channels. Journal of the American Water Resources Association 43: 72-85.

Winter, T. C., J. W. Harvey, O. L. Franke, and W. M. Alley. 1998. Ground Water and surface water-A single resource: U.S. Geological Survey Circular 1139.

Wolock, D. M. 2003. Base-flow index grid for the conterminous United States. U.S. Geological Survey Open-File Report: 03-263 . U.S. Geological Survey, Reston, VA. http://water.usgs.gov/lookup/getspatial?bfi48grd . Accessed August 2010.

Zimmerman, J. and A. Lester. 2006. Spatial distribution of hydrologic alteration and fragmentation among tributaries of the Connecticut River. The Nature Conservancy, Connecticut River Program. Northampton, MA (unpublished report).