DEVELOPMENT OF A CONCEPTUAL PLAN FOR A LIVING SHORELINE NEAR HARRISON AVE, CAMDEN NJ

Final report for New Jersey Coastal Zone

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Development of a Conceptual Plan for a Living Shoreline near Harrison Avenue in North Camden, New Jersey

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Prepared for:

NJCZ

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The views expressed herein are those of the author(s) and do not necessarily reflect those of the U.S. Department of Commerce, NOAA, nor the NJ DEP.
Established in 1996, the Partnership for the Delaware Estuary is a non-profit organization based in Wilmington, Delaware. The Partnership manages the Delaware Estuary Program, one of 28 estuaries recognized by the U.S. Congress for its national significance under the Clean Water Act. PDE is the only tri-state, multi-agency National Estuary Program in the country. In collaboration with a broad spectrum of governmental agencies, non-profit corporations, businesses, and citizens, the Partnership works to implement the Delaware Estuary’s Comprehensive Conservation Management Plan to restore and protect the natural and economic resources of the Delaware Estuary and its tributaries.
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Confidential Data

New Jersey listed rare species may have been encountered during the course of this project. The exact locations of any sensitive species are not reported here due to their confidential nature. If rare or sensitive taxa were encountered, specific location data will be furnished to New Jersey DEP in compliance with data sharing and collecting permit terms agreed between the Partnership for the Delaware Estuary and the State of New Jersey.

Suggested Method for Citing this Report.

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Executive Summary

In 2007, the Partnership for the Delaware Estuary (PDE) launched the Delaware Estuary Living Shoreline Initiative (DELSI), an interstate and collaborative effort to develop and implement new tactics for stemming erosion and enhancing the ecology of tidally influenced shorelines around the Delaware Estuary and to share our lessons learned with coastal managers, restoration practitioners, and the public (see, http://delawareestuary.org/living-shorelines). Until recently, tactics that we have developed (mainly in collaboration with the Rutgers Haskin Shellfish Research Laboratory) have mainly addressed shoreline degradation along salt marshes of Delaware Bay. Here, we provide our first conceptual ideas for a living shoreline tailored for the unique stressors and natural resources found within the urban corridor, namely along a degraded shoreline adjacent to a former landfill in North Camden, New Jersey.

The Harrison Avenue Landfill site is situated at the confluence of the Cooper River and Delaware River, on the eastern side of Petty Island. Although past industrial activity has left this landscape scarred and altered significantly, in most areas the natural infrastructure has begun to reassert itself as industrial uses have been reduced over time. The living shoreline conceived here would be situated along the eastern shoreline of the Delaware River immediately upstream from the mouth of the Cooper River. A fundamental principle of DELSI is to identify naturally resilient properties of plants, animals and their ecological relationships that can be marshalled to stabilize and strengthen coastal landscapes. In this area, fine muds have collected and nationally rare tidal freshwater wetlands have begun to develop. Earlier surveys by PDE staff also had detected a remnant community of native freshwater mussels, our nation’s most imperiled fauna. To develop a conceptual plan for a living shoreline at the Harrison Landfill site, we characterized the extent and types of existing plant and animal resources at the site using various GIS-based survey approaches.

The conceptual plan for the Harrison Landfill Living Shoreline is novel, designed as a habitat mosaic that would include freshwater tidal high marsh (not currently in evidence at the site), expanded freshwater tidal low marsh (exists currently but with low biodiversity), and beds of freshwater mussels and submerged aquatic vegetation in the shallow subtidal zone afronting the tidal wetlands. These habitats would be developed by some mix of the following: limited regrading of the site, repositioning of existing course woody debris and fill, and plantings of vegetation. With appropriate engineering to enhance bottom stability, substrate type, and hydrology, it is expected that existing seedstock for plants and broodstock for animals will allow natural colonization and population expansion for most target organisms over time.

If successful, it is estimated that the existing freshwater tidal wetland would be much more resilient, productive, and would furnish significantly greater ecosystem services such as wave attenuation, fish and wildlife habitat support, and water quality enhancement. Filtration of water by the associated bed of
freshwater mussels (and perhaps also SAV) would eventually increase from the current 1.1 million gallons per day (MGD) to between 3.3-14.4 MGD, depending on mussel densities that can be reached. The concomitant removal of total suspended solids would increase from the current 15.8 metric tons per year to between 46-199 metric tons per year, as well as increased removal of associated particulate forms of nutrient pollution. If successful, the living shoreline project would therefore likely contribute to a substantial increase in meaningfull water quality benefits in the Camden area at the former landfill site. In addition, since rare freshwater mussel species tend to occur within healthy beds of abundant common species, this project would also likely expand the available habitat for state listed species such as *Leptodea ochracea*, *Lampsilis cariosa*, and *Ligumia nasuta*, which appear to currently be constrained by limited suitable bottom habitat and a lack of abundant common mussel species. Hence, living shorelines in the urban corridor that contain a mosaic of habitats may benefit state heritage species of animals as well as rare freshwater tidal wetland plants and water quality.

### Introduction

**Living Shorelines**

A living shoreline is a method of shoreline stabilization that protects the coast from erosion while also preserving or enhancing environmental conditions (Smith 2006, PDE 2012). Different types of living shorelines vary in effectiveness and ecological value. Single tactics can be used on their own in low energy areas, or combined as hybrids in tandem with hard tactics for higher energy sites. For example, subtidal breakwaters or sills can be constructed to dampen wave energy and currents, allowing for intertidal biological enhancements. A levee can be strengthened by establishing tidal marsh in front of it. In areas where rising sea levels threaten to release contaminants sequestered along shore, living shorelines can also be used to stabilize or cap contaminated sites. Every site is different, and the type of living shoreline selected must be tailored to local physical, chemical and biological conditions. Living shorelines are a relatively new innovative approach, not yet as predictable or standardized as their hard-structure counterparts. Some tactics have more predictable outcomes than others. Implementation costs are often less expensive than hard tactics, although the long-term efficacy and maintenance costs have yet to be fully assessed. Therefore, the type of living shoreline selected should also depend on the degree of risk that can be tolerated, the management goals, as well as projected cost:benefit ratios over longer time horizons, in comparison to traditional tactics (PDE 2012a).

PDE has had significant success with using living shorelines to stem erosion on the Maurice River along the Delaware Bayshore Region of New Jersey. PDE worked with Rutgers University to develop a new, tailor-made tactic that incorporates plants, animals (shellfish) and natural products to slow erosion and enhance tidal marsh communities (PDE 2011). That project and subsequent estuary-wide planning and assessment efforts have generated a great deal of information about tactics and options to help boost the likelihood of success of future living shoreline projects. More information about living shorelines, the Maurice River project, and the estuary-wide planning effort can be found at [http://delawareestuary.org/Living_Shorelines](http://delawareestuary.org/Living_Shorelines).
**Living Shorelines Benefits**

Living shorelines create and protect tidal wetlands and other sensitive coastal habitats such as submerged grass beds and beaches. Sea level rise presents numerous challenges for preserving critical natural habitats and protecting people and communities located along the Delaware River, which is tidally influenced as far up river as Trenton, New Jersey. Chief among these is the potential loss of wetlands due to climate change and rising seas often exacerbated by other anthropogenic stressors such as pollution, altered hyrology and. Modeling completed by Industrial Economics in 2010 for the Partnership for the Delaware Estuary indicates that with 1 meter of sea level rise, over 42,500 hectares of tidal wetlands – about one-quarter of the total in the estuary – is likely to be lost to conversion by 2100 (PDE 2010). This loss of tidal wetlands will be especially disastrous since it will make local communities even more vulnerable to storms and sea level. In addition, channel deepening within the urban corridor has the potential to alter tidal hydrodynamics, volumes and sediment supply, potentially altering shoreline erosion or tidal range. Coastal wetlands are one of the Delaware Estuary’s most important and characteristic habitats, and they are a premier environmental indicator for the area’s ecosystem. In the urban corridor between Trenton and Paulsboro, NJ, the coastal wetlands usually take the form of freshwater tidal marshes, which are nationally rare. Only about 5% of the Delaware Estuary’s freshwater tidal wetlands remain. These rare wetlands are a top PDE priority for protection, enhancement and restoration. Much attention is paid to coastal wetlands in areas closer to Delaware Bay, however very little work has been done to help secure the important wetlands located along vulnerable urban communities lining the more northern parts of the Delaware River, such as Camden. Living shorelines can help increase and protect the wetlands that benefit Camden and the region. Therefore, developing innovative, practical solutions for helping marshes adapt to sea level rise, and building the understanding within local communities for how important it is to maintain tidal wetlands using these tactics is critical.

**Living Shoreline Hybrid Mosaic**

In addition to the prospects of enhancing rare and important freshwater tidal marshes, living shorelines along urban riverfronts could potentially benefit other rare and important shallow subtidal habitats such as beds of freshwater mussels and submerged aquatic vegetation (SAV). Both freshwater mussels and SAV beds are widely regarded as providing important ecosystem services related to water quality improvement, sediment stabilization, and habitat enrichment for fish and crustaceans.

A living shoreline design that can incorporate mussels and SAV into the design would help to address multiple conservation and restoration goals, including rare species protection, water quality enhancement, and habitat restoration. Freshwater mussels are the most imperiled North American biota, including in the Delaware River Basin (Table 1). Healthy beds of submerged mussels and SAV in shallow subtidal zones might also help to dampen wave energy reaching the shoreline. Living shorelines can create a habitat mosaic by having multiple habitat targets that function in ecologically synergistic ways. For this study, we targeted an area where a hybrid living shoreline design could have the greatest benefit, including enhancements for tidal freshwater wetlands, freshwater mussel beds, and SAV beds. We envision a living shoreline “habitat mosaic,” which grades from upland communities to intertidal marshes to subtidal SAV/mussel beds, perhaps bounded at the seaward edge by perforated subtidal rock sills.
(using existing fill material on site) that permit free movements of fish but which help to hold courser sediments and abate waves and currents.

**Table 1.** List of species of freshwater mussels that are native to the Delaware River Basin and their current conservation status listing within three of the basin states, Delaware, New Jersey and Pennsylvania.
It was long thought that the urban Delaware River system was too degraded to contain substantial populations of either native freshwater mussels or submerged aquatic vegetation (SAV). But over the last 3 years, PDE and partners have discovered substantial beds of at least 7 species of freshwater mussels in numerous locations along the Delaware River between Trenton and Camden, including species believed to be locally extinct (Fig. 1) mussel densities appear greatest where SAV also grew. The decline of bivalve biodiversity and abundance and the ecosystem services they provide, such as biofiltration, signifies a drop in environmental integrity at both local and watershed scales. Freshwater mussels and marine bivalves (such as oysters, scallops and clams) are often the dominant functional component in aquatic food webs from the headwaters to the coast, improving water quality, enriching sediments, and adding habitat complexity (Table 2). Estimated summertime water processing rates in the Delaware Estuary by eastern oysters (~10 billion L/h), a freshwater mussel species (~10 billion L/h), and an estuarine mussel (~60 billion L/h) suggests that populations of all three species furnish important services across the entire freshwater to estuarine gradient (Bergstrom, 2011). Unfortunately, all three bivalves are severely threatened by changing conditions (PDE, 2010), and are likely far below their potential carrying capacities.

Benthic surveys by PDE and EPA in 2008-2009 also found many areas with considerable SAV which may live in mutualism with freshwater mussels. As voracious filter-feeders, freshwater mussels also remove significant suspended particulate matter, thereby increasing water clarity and light availability for...
SAV on the bottom. Our quantitative surveys in 2012 revealed a positive relationship between mussel abundance and the presence of SAV (PDE 2013)

**Table 2.** Some ecosystem benefits of key types of bivalve shellfish in the Delaware Estuary, and their relative importance (number of check marks).

<table>
<thead>
<tr>
<th>Importance of Shellfish to the Delaware Estuary Watershed</th>
<th>Oysters Crassostrea virginica</th>
<th>Marsh Mussels Geukenia demissa</th>
<th>FW Mussels Elliptio complanata</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Commercial</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structural Habitat</td>
<td>✓    ✓    ✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Prey</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Ecological</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biofiltration</td>
<td>✓    ✓    ✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Top-down grazing, TSS removal, light</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Biogeochemistry</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Enrichment/turnover, benthic production</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Shoreline Protection - nearshore reefs</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Shoreline Stabilization - living edges</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Cultural-Historical</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waterman Lifestyle, Ecotourism</td>
<td>✓    ✓    ✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Native American - jewelry, dietary staple</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Bioindicator</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Watershed Indicators</td>
<td>✓    ✓    ✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Hallmark resource status/trends</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Site-specific Bioassessment</td>
<td>✓    ✓    ✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>NS&amp;T, caged sentinels</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Conservation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biodiversity</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>FW mussels most critically impaired biota</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

**Goals**

The primary goal of this project was to expand the Delaware Estuary Living Shoreline Initiative into the urban corridor, as envisioned in our earlier planning study for New Jersey, which was funded by the Dodge Foundation (PDE 2012a). Although we have long regarded living shorelines as an important tactic to help our region adapt to climate change (PDE 2010), this message has been more widely received since Superstorm Sandy. Numerous efforts are now underway by us and others to install more living shoreline projects around Delaware Bay and in neighboring estuaries; however, to our knowledge no living shorelines have been designed or implemented in the freshwater tidal portion of the Delaware River Basin. To prepare a conceptual design for this part of the system, a secondary goal was to assess existing plant and animal populations that could be included in our habitat mosaic type of project. Finally, another objective was to participate in community or partner meetings to begin to build awareness of the opportunities for living shoreline projects such as the one we conceived and their associated costs and benefits.
**Approach**

To achieve our objectives, the following tasks were completed:

Task 1: Selected a study site based on discussions with regional leaders and managers.

Task 2: Performed on-the-ground site reconnaissance to assess baseline physical, chemical and biological features that could be important for the conceptual design of a living shoreline.

Task 3: Conducted freshwater mussel and SAV surveys in the vicinity of the site to fill vital data gaps and assess whether broodstock exist at the site to facilitate colonization by target biota.

Task 4: Participated in meetings with local leaders and community stakeholders to raise awareness and interest in living shorelines as a way to enhance water quality, flood protection, and fish production.

Task 5: Developed conceptual plans for various living shoreline options at the selected study sites, which provide the basis for more detailed site plans and funding applications.

Task 6: Disseminated results through meetings and/or written materials to state/local authorities and local partners.

**Methods**

Methods are described below for Tasks 2 (site assessment), 3 (benthic biota surveys) and 5 (living shoreline conceptual plan).

**Site Reconnaissance**

Physical, chemical and biological features that could be important for the conceptual design of a living shoreline were assessed along the shoreline abutting the old Harrison Avenue Landfill where an array of restoration projects are currently underway within the former uplands of the landfill proper. On-the-ground reconnaissance at the site consisted of measuring elevation, recording vegetation and substrate type, and evaluating energy, erosion, and other abiotic factors to confirm suitability for a living shoreline project.

A Real Time Kinetic Geographic Positioning System (RTK GPS, Tremble R6) was used to characterize local site conditions. The RTK GPS was a Virtual Reference Station (VRS) single rover and data collector that had one-centimeter horizontal and two-centimeter vertical accuracy.

Elevation data collected with the RTK GPS was imported into ArcGIS (Version 10.2) to create elevation contours along the shoreline. GPS points were taken randomly and along transects from the shoreline to the water line at low tide. The substrate and vegetation types were recorded at each point. Contours within optimal planting zones with the appropriate vegetation were used to guide the potential installation. In previous living shoreline installations, determining the elevation of any installed materials was found to be one of the most critical factors to be considered to facilitate establishment of viable

vegetated wetlands. The area within these planting zones was used to calculate the area of marsh that could be potentially created post installation.

Other data collected during the field assessment included: a characterization of energy conditions, specifically looking at the presence of boat wakes, average fetch, and other field observations; landscape condition, including surrounding development, barriers to landward wetland migration, riparian land use, native versus invasive plants, and soil condition; percent of shoreline alterations and shoreline control structures; and approximate shoreline erosion/stability.

Baseline biotic conditions were also assessed along the Harrison Landfill shoreline, as within the tidally-influenced and non-tidal areas of the Cooper River Watershed (see sections below) to fill vital data gaps and assess whether broodstock exist at the site to facilitate colonization by target biota. Surveys for freshwater mussels and submerged aquatic vegetation (SAV) can be foundational taxa in shallow freshwater tidal habitats because they are habitat-forming “ecosystem engineers” that enrich structural ecology for other species, stabilize the bottom, and help sustain water quality. When healthy and dense, mussel and SAV beds also have the potential to buffer adjacent freshwater tidal wetlands from swift currents and possibly waves depending on tide stage.

**Harrison Shoreline Biotic Survey**

The presence and relative abundance of freshwater mussels and SAV were assessed along the shoreline abutting the Harrison Avenue Landfill (Fig. 2) on September 10, 2013. A semi-quantitative search approach was adopted to maximize coverage while also providing limited information about population robustness and extent.

The survey approach was a timed search method whereby three trained mussel/SAV surveyors snorkeled at low tide (allowing for maximum depth coverage and visibility) from fixed points that were marked with 8 foot PVC marker poles. The GPS locations of surveyed areas were recorded.

![Figure 2. Map showing the locations of sample points for freshwater mussel and submerged aquatic vegetation surveys conducted on September 10, 2013 at the confluence of the Cooper and Delaware Rivers, New Jersey.](image)
For each point, 1-3 surveyors snorkeled for up to 20 minutes in concentric circles around the pole (Figs. 3, 4), and then they recorded the search time and observations on bottom type (grain size, presence of debris, SAV coverage, etc). Any shells or live mussels encountered were hand collected, placed in mesh collecting bags, and taken to the nearby boat where a second team of two scientists measured shell heights and recorded mussel species (Fig. 5). All sampled mussels were then returned unharmed to the locations where they had been collected.

PDE maintained a NJ scientific collecting permit for the areas searched during this project. All surveyors were trained in mussel survey methods by Dr. D. Kreeger who has nearly 30 years of experience and is a member of the Pennsylvania Biological Survey, Mollusk Subcommittee. Species identifications by Dr. Kreeger were based on voucher specimens previously collected for Delaware River taxa, which have been confirmed by Dr. Art Bogan (North Carolina State Museum of Natural History), an internationally regarded unionid taxonomist.

Our objective in the 2013 mussel/SAV survey was to build upon preliminary anecdotal information about the locations of rare mussel taxa that had recently been discovered in the immediate area. Shells from five native species of mussels, including two that are listed in the State of New Jersey as rare, had been found.
at the site, but our goals were to confirm whether live specimens existed and to delineate the boundaries of any mussel beds. For this report, we listed the species that were found but we do not show the exact locations for any state-protected species.

**Cooper River Mussel Surveys**

In addition to the semi-quantitative mussel and SAV surveys conducted along the Harrison Landfill shoreline near the mouth of the Cooper River (see above, September 10, 2014), additional mussel surveys were performed within the Cooper River using a qualitative approach. On September 27, 2013, PDE staff and local volunteers toured the tidal freshwater zone of the Cooper River from the mouth upstream to the head of tide at Kaighn’s Avenue Dam in Camden, NJ. The presence and absence of freshwater mussels (including shells) was examined at ten locations (Fig. 6). Qualitative surveys are rapid surveys that can adaptively switch best possible survey methods and equipment to optimize data outputs despite changing weather and habitat conditions. Qualitative searches yield important data to delineate the range of mussel populations, and are useful for pinpointing locations of rare taxa or large beds for more intensive studies. Data from qualitative searches include presence/absence and as well as catch per unit effort, which can help identify spatial differences in mussel richness and abundance.

At each of ten locations, 20 to 60 person-minutes were spent looking for live mussels or shells (Fig. 7). The timing of field efforts was generally centered on low tide, often extending for six to eight hours between early ebb tide and late flood tide. When the tide was higher or if visibility was marginal, beach walks were performed for shells. Although shells can wash into a shoreline reach from upstream, locations
that had many shells or hinged shell pairs were indicative that living mussel beds existed in the vicinity, often leading to more focused searches in those areas. All surveyors were trained in methods for identifying living mussels buried within the substrate as well as differentiating native freshwater mussels from invasive Asian clams, *Corbicula fluminea*. The total time at each study area varied, and was tailored for the length of available shoreline that was accessible and could serve as mussel habitat.

In addition to the kayak surveys of the lower Cooper River and the semi-quantitative searches along the Harrison Landfill shoreline (see above), on July 15, 2013, PDE staff performed exploratory mussel surveys in a few non-tidal reaches of the Cooper River in the vicinity of Cherry Hill, New Jersey. These surveys were part of a mussel survey training workshop with participants mainly from the Rutgers Cooperative Extension of Burlington and Camden Counties. Approximately fifteen novice mussel surveyors were taught about the ecological importance of freshwater mussels and their present conservation status by D. Kreeger and D. Ross, and then led on mussel surveys in the stream for a period of approximately 2 hours (Fig. 8).

**Data Analysis and Statistics**

Semi-quantitative mussel survey data from the Harrison shoreline were statistically examined using parametric procedures to test for relative spatial differences in mussel density and richness among four zones adjacent to the Harrison Landfill shoreline in North Camden, New Jersey (Fig. 9). The four zones were in the Cooper River (Cooper), at the Cooper River Mouth (Mouth), at the confluence of the Delaware and Cooper Rivers (Confluence) and upstream from the confluence along the Delaware River (Delaware). Statistical tests were performed with Statgraphics Centurion (Version XVI). In some cases, data were transformed prior to statistical analyses to achieve normal data distribution and satisfy assumptions of equal variances among means.
Estimate of Mussel-Mediated Water Quality Benefits

Like their marine counterparts (oysters, clams, mussels), freshwater mussels filter tremendous quantities of water and remove fine particles to satisfy their nutritional demands. In doing so, they promote clearer water which benefits bottom plants and benthic algae by increasing light availability. Particle filtration also represents an importance service for water quality since high levels of total suspended solids (TSS) and associated nutrients (nitrogen, phosphorus) are primary sources of impairment, especially in urban landscapes such as Camden, New Jersey.

The importance of freshwater mussel beds to water quality can be estimated by directly comparing datasets for mussel population demographics (abundance, size classes, species), mussel physiological processing rates (clearance, filtration, assimilation), and available food supply (e.g. TSS concentrations). Insufficient data exists for physiological rate functions of mussels of the tidal Delaware River, food conditions, and seasonality, to provide a refined estimate, but here we applied literature values and best judgment as a proxy for local data that we aim to collect in the future contingent on funding. For the purposes of this exercise, we also limit our water quality examination to estimates of TSS removal and bulk water processing by the collective array of species that were found at the Harrison shoreline site.

To estimate the collective water clearance rates and TSS filtration rates of mussels at the site, it was important to first estimate their tissue dry mass. Mussels were not sacrificed in this study, and hence we relied on a large body of data from previous studies performed by D. Kreeger between 2000 and 2011 wherein regression equations were derived that predict dry tissue weight from measured shell height for eleven species of freshwater mussels. Species-specific allometric relationships had also been developed for five of the six species encountered during the 2013 survey (see Kreeger et al. 2013 for method). To predict dry tissue weights for the sixth species, a general allometric equation was derived for 653 mussels representing all eleven mussel species (see and which included representatives of Atlantic, Mississippi, and Pacific Slope assemblages. Following standard allometric protocols, shell height and dry tissue weight data were transformed by natural logarithm, and then contrasted by linear regression. Appropriate equations were then applied to predict the dry tissue weight for each individual mussel that was collected.
and sized during the 2013 survey (n=178). Summary data for mussel number and estimated total dry tissue weight was then calculated per estimate of bottom area searched per sampled point circle.

Existing literature on typical clearance rates for freshwater mussels was scrutinized for data that are scaled for dry tissue weights. Compared to marine bivalves, there is remarkably little data on their physiological rate functions, and in the studies that have been conducted few researchers have obtained dry tissue weight data (often because of the desire or need to not to kill the animals). For the purposes of this study, only reported weight-specific clearance rates were examined, and these are summarized in Table 3. Clearance rate data for studies of natural diet utilization are preferred because they best represent natural conditions. Due to the rarity of suitable studies, however, we used all available weight-specific data. In general, for a given temperature and diet, different species of freshwater mussels have similar weight-specific clearance rates (Kreeger 2011). The average clearance rate from these studies was 0.875 liters per hour per gram dry tissue weight (Table 9).

**Table 3.** List of known clearance rate data that can be scaled to mussel dry tissue weights (from Bergstrom et al. 2013).

<table>
<thead>
<tr>
<th>Study</th>
<th>Number of Species</th>
<th>Diet</th>
<th>Clearance Rate (L h⁻¹ g⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kryger and Riisgard (1988)</td>
<td>4</td>
<td>lab algae</td>
<td>1.11</td>
</tr>
<tr>
<td>Pusch et al. (2001)</td>
<td>2</td>
<td>field seston</td>
<td>0.38</td>
</tr>
<tr>
<td>Gatenby (2000)</td>
<td>3</td>
<td>lab algae</td>
<td>1.72</td>
</tr>
<tr>
<td>Silverman et al. (1995, 1997)</td>
<td>5</td>
<td>lab bacteria</td>
<td>0.77</td>
</tr>
<tr>
<td>Patterson (1984)</td>
<td>1</td>
<td>lab algae</td>
<td>0.38</td>
</tr>
<tr>
<td>Vanderploeg et al. (1995)</td>
<td>1</td>
<td>lab algae</td>
<td>1.45</td>
</tr>
<tr>
<td>Gatenby &amp; Kreeger (2003)</td>
<td>6</td>
<td>field seston, lab algae</td>
<td>0.23</td>
</tr>
<tr>
<td>Kreeger (2011)</td>
<td>3</td>
<td>field seston</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Mean &gt;</strong> 0.875</td>
</tr>
</tbody>
</table>

To avoid confusion, the term **clearance rate** refers to the volume of water that is cleared of particles, which is typically derived from the rate of particle disappearance per unit time and volume. The term **filtration rate** refers to the actual rate of removal of discrete weights of particles, which is typically calculated by multiplying the clearance rate times the particle concentration. Particle filtration rates can be applied to a variety of seston characteristics, including dry weight of particles, carbon, chlorophyll, etc. For the purposes of this study, it was assumed that the typical concentration of total suspended material in the size range that can be filtered by bivalves was 10 mg/L in the area of the Delaware River where the survey was performed.
Mussel densities and estimated dry tissue weights were summed per sampled point, divided by the search CPUE and averaged across each site. Average mussel densities and weights were then estimated for the approximate area that was searched (i.e., the area of the polygon bounded by the mean low tide shoreline and seaward transect terminus), extrapolated to the total area of expected suitable habitat at the site, resulting in an estimated total mussel number and dry tissue mass for the site. Representative weight-specific clearance rates were then compared to the total dry tissue biomass of mussels to estimate the combined water processing rate for extant mussels living in the shallow subaqueous zone at the site currently.

To gauge whether the population size of this mussel bed might be able to be enhanced by habitat restoration such as with a living shoreline, we contrasted the mussel population biomass currently at the site with mussel population biomass (per unit area) for four other representative mussel beds of the tidal freshwater Delaware River, which were examined similarly in 2012 (Kreeger et al. 2013). The four other sites sampled previously span an array of shoreline types and having both relatively degraded mussel beds (low richness, low density) and healthier beds (higher richness, density, presence of juveniles); hence, we regard the mean density and tissue biomass at these sites as representative of the typical (not maximum) carrying capacity for Delaware River tidal shorelines. It is important to note that this is a conservative assumption of carrying capacity because even those sites might merit enhancement, possibly resulting in added carrying capacity there too. But for the purposes of this report, we conservatively contrasted the difference between the existing mussel density and tissue biomass at the Harrison site and the average mussel density and tissue biomass for four other representative mussel beds. This difference serves as an estimate of the potential “uplift” in mussel population biomass that might be achieved at the Harrison site if it was modified to boost mussel carrying capacity to be in line with the other surveyed sites that contain mussels.

For both the current and potential future estimates of mussel bed sizes at the Harrison site, we then predicted the population-level clearance rates (L/hour). Assuming typical concentrations of total suspended solids (TSS) in this reach of the Delaware River are 10 mg/L, we estimated the current (and potential future) filtration rate (weight of TSS filtered per unit time) as a proxy for water quality services rendered by the mussels. Actual processing of nutrients by the mussels (and SAV) warrant more study before similar estimates can be made.

**Living Shoreline Conceptual Plan**

Geospatial data collected using the Real-Time Kinematic Global Positioning System (RTK-GPS) was imported into ArcGIS where it was evaluated to determine the latitude, longitude, and elevation of each point collected.

Data were reported in the NAD 88 and NAVD 88, whose zero mark is at mean sea level for North America, and was projected in the Delaware State Plane coordinate system. A Triangulated Irregular Network (TIN) was created using the Create TIN tool. A TIN creates a continuous surface from a set of individual points, depicting changes in elevation across the interpolated surface. Subsequently, the Surface Contour tool in the 3D Analyst extension was used to create surface elevation contour lines from
the TIN across the intertidal and supratidal mudflat and nearshore upland. The contour lines were used to place Mean Higher High Water (MHHW, 1.01m), Mean High Water (MHW, 0.89m), Mean Low Water (MLW, -1.01), and Mean Lower Low Water (MLLW, -1.07) at their correct elevations along the site based on local elevations as reported in NOAA Technical Memorandum NOS CS 15, VDatum for the Chesapeake Bay, Delaware Bay, And Adjacent Coastal Water Areas (Zhizhang et al, 2008).

For the purposes of this project and existing site conditions, a conceptual design for a hybrid mosaic type of living shoreline was drafted that would include one or more of the following four habitat types; low marsh, high marsh island, subaqueous mussel/SAV beds, and high marsh/upland grading. To convey the options best, each habitat component is separately presented using both overhead and profile views. Overhead views depict the placement of the created habitat within the context of the entire site as well as the tidal elevations. Profile views illustrate the correct position of each habitat type, as well as associated flora and fauna, within the local tidal prism. Before and after conceptual designs were created to illustrate the change in habitat that is being recommended. Living shoreline conceptual designs were constructed using Adobe Illustrator CS5.

**Results and Discussion**

**Site Selection**

Potential living shoreline projects have been discussed for numerous locations within Camden, New Jersey. For this study where we planned to develop a conceptual design for one prospective site, we initially needed to choose among the various candidate locations. To assist with this site selection and learn more about local interests and needs, PDE convened several living shoreline workshops within New Jersey in 2012 and 2013. Participants were generally from the private sector and state and federal agencies. Participants were able to ask questions about places that were important to them. Camden was one area that many participants

![Figure 10. Aerial photo of the Harrison Avenue Landfill site at the mouth of the Cooper River in North Camden, New Jersey, during early 2013 after site remediation had commenced on the upland portion (Photo courtesy: Frank McLaughlin, NJDEP).](image-url)
thought would benefit from a living shoreline project.

In order to determine suitable sites within or near Camden for a living shoreline project, meetings were set up with the NJ Department of Environmental Protection and Rutgers to tour candidate sites. Two of the leading sites were the Harrison Landfill Site and Phoenix Park restoration project. For this project, the Harrison Landfill Site was chosen for further field reconnaissance because large upland restoration projects had already begun there and a living shoreline would be a good addition to activities that are already well underway (Fig. 10). Furthermore, the prospects for funding for a subsequent living shoreline installation were considered to be more likely and sooner.

**Site Reconnaissance**

Results from the RTK-GPS survey indicated that the Harrison Landfill shoreline was characterized mainly by a vast intertidal mudflat between MHHW and MLLW with a typical elevation difference of 2.08 meters. This large expanse provides the necessary area to construct a mosaic of interconnected habitats. The elevation range allows for the placement of materials to build complex topographic features in close proximity to mimic the natural hummock/hollow profile of marshlands. The locale consists primarily of deep, fine substrates (silt mainly) interspersed with a network of intertwining creeks. These creeks offer established drainage channels which can be utilized as natural barriers to constructed features to prevent wash out of assembled vegetation areas due to the shear stress from sheet flow run-off. The mudflat is currently populated by a monoculture of *Nuphar*, a succulent vascular plant that is very common as a low marsh dominant species in freshwater tidal wetlands of the Delaware Estuary (Fig 11), with small, isolated patches of Arrow arum and water lily growing near the landward margin. The supra-littoral and riparian zones consist of a barren fringing low grade sloped area and a steep upland vegetated slope leading to the landfill platform. A diverse array of course debris exists along the base of this steep slope, including, rock, eroded trees, and anthropogenic sourced refuse from the old landfill (Fig.12). Some of the course materials existing at the site (rock, concrete, and trees) may be suitable for recycling and reuse as stabilizing components of constructed habitats within the living shoreline. Course materials such as these have the potential to provide complexity, help to divert flows and tidal energies, and can stabilize shifting substrates to the benefit of benthic producers and sessile fauna.

![Figure 11. Picture of the intertidal mudflat at the Harrison Avenue Landfill site. The mudflat is colonized by a monoculture of Nuphar.](image)

![Figure 12. Rubble collected along the low grade slope from the intertidal mudflat to the steep slope leading to the landfill.](image)
**Harrison Shoreline Biota Surveys**

Seventeen locations were searched at the Harrison Landfill shoreline in North Camden for freshwater mussels and submerged aquatic vegetation (SAV). Search times varied between 10 and 81 person-minutes per location. Very little SAV was found at the site, and we focus on results of the mussel surveys.

Six native species of freshwater mussels were found alive (Fig. 13). This richness represents half of the total number of species that have been historically recorded across the Delaware River Basin, and three of the species are listed by the State of New Jersey as Threatened. The species recorded were: *Elliptio complanata*, *Pyganodon cataracta*, *Anodonta implicata*, *Lampsilis cariosa*, *Leptodea ochracea*, and *Ligumia nasuta*. To protect the exact locations for rare taxa, here we report only the total richness across the surveyed areas of the site (Fig. 14). In general, more species were associated with the mouth of the lower Cooper River and confluence area than were associated with the Delaware River channel behind Petty Island.

![Examples of live freshwater mussels and shells collected at the Harrison Landfill shoreline site, north Camden, NJ, on April 3, 2013 and September 10, 2014. (Photos: D. Kreeger).](image)
The relative abundance of live mussels, as surveyed with the semi-quantitative approach, also pointed to higher densities associated with the mouth of the Cooper River and the Confluence area where the Cooper and Delaware Rivers meet (Fig. 15). A one-way analysis of variance comparing the four search areas was not significant (p>0.05) due to high variability. The number of mussels found per minute averaged 0.92 at the Cooper Mouth, 0.79 at the Confluence, 0.54 along the Delaware River side, and 0.22 along the lower Cooper River.

It is difficult to compare these semi-quantitative (mussels/minute) data to outcomes of recent quantitative searches (mussels/m²) that have been performed for freshwater mussels upstream in the tidal freshwater zone of the Delaware River (Kreeger et al. 2013). Assuming 5 square meters were typically well searched per person per 10 minutes, the densities per square meter at the Harrison Landfill site averaged 1.8 at the Cooper Mouth, 1.6 at the Confluence, 1.1 along the Delaware River side, and 0.4 along the lower Cooper River. These densities were well below densities that were quantitatively searched at four sites upriver on the tidal Delaware River (Kreeger et al. 2013), which averaged from 5 to 30 mussels per square meter.
Although the densities of mussels at the Harrison Landfill site were lower than other mussel beds surveyed in the Delaware River, the species richness and typical sizes were comparable to the other sites. Mussel species richness varied from 0 to 6 among the 17 survey locations, indicating that all size species were found together at least at one location. In our previous surveys of the tidal Delaware River, mussel species richness was positively associated with overall density and biomass. Rare species were only found associated with large numbers of more common species in that study, suggesting that high overall densities may help to modify conditions allowing for rare taxa to exit, possibly by helping stabilize bottom conditions. More mussels tended to be found in the lower mouth of the Cooper River and the Confluence of the Delaware and Cooper Rivers than along the main axis of the rivers (Fig. 16).

![Box and whisker plot showing medians and 25% quartiles for the relative catch per unit effort (mussels/minute) compared among four search areas (see Fig. 9) at the Harrison Landfill shoreline, North Camden, New Jersey, on September 10, 2013.](image-url)

**Figure 16.** Box and whisker plot showing medians and 25% quartiles for the relative catch per unit effort (mussels/minute) compared among four search areas (see Fig. 9) at the Harrison Landfill shoreline, North Camden, New Jersey, on September 10, 2013.
Species richness and sizes of mussels appeared to be comparable to mussel populations surveyed upstream in the tidal Delaware River (Kreeger et al. 2013). The total number of each species surveyed and their average shell heights were as follows: *Elliptio complanata* (n=48, mean height=85.5 mm, SE ±2.0 mm); *Pyganodon cataracta*, (n=47, mean height=109.9 mm, SE ±2.0 mm); *Anodonta implicata*, (n=70, mean height=98.5 mm, SE ±1.7 mm); *Lampsilis cariosa*, (n=4, mean height=62.4 mm, SE ±7.0 mm); *Leptodea ochracea*, (n=11, mean height=60.9 mm, SE ±4.2 mm); and *Ligumia nasuta* (n=2, mean height=84.1 mm, SE ±9.9 mm). Therefore, the two floater species (*A. implicata* and *P. cataracta*) were largest sized (Fig. 17). Shell heights for the 177 mussels surveyed at the Harrison site averaged 94.5 mm for all six species combined. The largest mussels by species (Fig. 17) were eastern floaters, *Pyganodon cataracta* (mean ±SE; 108.8 ± 2.0 mm, n=42), which were significantly larger than all other species (ANOVA, p<0.05).

![Figure 17. Box and whisker plot showing medians and 25% quartiles for the shell heights of six species of freshwater mussels surveyed at the Harrison Landfill shoreline, North Camden, New Jersey, on September 10, 2013.](image-url)
Estimated mean dry tissue weights (see methods) for the six species surveyed (Fig. 18) were as follows: *Elliptio complanata* (2.1 g, SE ±0.3 g, n=48); *Pyganodon cataracta*, (7.7 g, SE ±0.3 g, n=47); *Anodonta implicata*, (3.3 g, SE ±0.3 g, n=70); *Lampsilis cariosa*, (1.9 g, SE±1.1 g, n=4); *Leptodea ochracea*, (2.5 g, SE±0.7 g, n=11); and *Ligumia nasuta* (1.9 g, SE±1.6 g, n=2).

When measured shell heights were used to estimate dry tissue mass per mussel (see methods), the sum biomass per species for all 178 live mussels sampled totaled 310 g for *P. cataracta*, 232 g for *A. implicata*, 99 g for *E. complanata*, 27 g for *L. ochracea*, 7.7 g for *L. cariosa* and 3.8 g for *L. nasuta*. Hence, the mussel assemblage at the Harrison Landfill site can be characterized as dominated by the two floater species in terms of tissue mass (80%), which is the best metric for predicting mussel-mediated ecosystem services (Fig. 19). Eastern elliptios comprised 14.6% of the total dry mussel tissues.
Estimated dry tissue weights for all mussels of any species are summarized per search area in Table 4. Larger sized mussels tended to be found at sites in the Confluence Zone (average = 8.9 g m$^{-2}$) compared to the Mouth (5.7 g m$^{-2}$), Delaware River (4.7 g m$^{-2}$), or Cooper River (1.2 g m$^{-2}$). This is not surprising since nexus areas between rivers tend to be rich in food supplies so long as the bottom habitat is not too degraded.

In comparison to our surveys of other areas of the tidal Delaware River, the densities of mussels and their associated dry tissue mass were low at the Harrison Landfill site. Across four zones, mussels averaged about 1.2 animals per square meter of bottom habitat. In contrast, four other nearshore, shallow subtidal shorelines were quantitatively searched for mussels in the tidal freshwater part of the Delaware River 2012 (Kreeger et al. 2013), and mean mussel densities averaged 5.5, 10.8, 18.3 and 30.2 per square meter at those four locations. Average dry tissue weights per square meter averaged between 9.8 and 76.4 grams among those four locations surveyed earlier, notably greater than the 5.1 gram per square meter at the Harrison site.
Table 4. Summary of freshwater mussel survey data for seventeen sites within four zones at the Harrison Landfill shoreline, North Camden, New Jersey, on September 10, 2013.

<table>
<thead>
<tr>
<th>Site</th>
<th>Zone</th>
<th>Catch per Unit Effort (mussels per min)</th>
<th>Estimated Search Area (m2)</th>
<th>Estimated Mussels per m2</th>
<th>Estimated Dry Tissue Weight (g m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>by Site by Zone</td>
<td></td>
<td>by Site by Zone</td>
<td>by Site by Zone</td>
</tr>
<tr>
<td>NJCOOPFM1</td>
<td>Cooper</td>
<td>0.0 5.0 22.8</td>
<td>0.0 0.4</td>
<td>0.0 0.7</td>
<td>1.2</td>
</tr>
<tr>
<td>NJCOOPFM2</td>
<td></td>
<td>0.4 40.5</td>
<td></td>
<td>0.9</td>
<td>2.3</td>
</tr>
<tr>
<td>NJCOOPFM3</td>
<td>Cooper Mouth</td>
<td>0.0 5.0 8.0</td>
<td>0.0 0.7</td>
<td>0.0 1.5</td>
<td>5.0</td>
</tr>
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<td>NJCOOPFM4</td>
<td></td>
<td>0.7 11.5</td>
<td></td>
<td>1.5</td>
<td>11.2</td>
</tr>
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<td>NJCOOPFM5</td>
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<td>2.0 5.5</td>
<td></td>
<td>4.0</td>
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</tr>
<tr>
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<td></td>
<td>1.0 10.0</td>
<td></td>
<td>1.9</td>
<td>6.5</td>
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<tr>
<td>NJCOOPFM8</td>
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<td></td>
<td>1.7</td>
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<tr>
<td>NJCOOPFM9</td>
<td></td>
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<td></td>
<td>2.5</td>
<td>12.8</td>
</tr>
<tr>
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<td></td>
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<td></td>
<td>0.6</td>
<td>3.9</td>
</tr>
<tr>
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<td></td>
<td>0.2</td>
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</tr>
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<td>3.8</td>
<td>19.4</td>
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<td></td>
<td>0.0 5.0</td>
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<td></td>
<td>0.7 8.1 10.4 1.4 1.2 6.0 5.1</td>
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<td>138.0</td>
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</table>
Cooper River Mussel Surveys

Surveys using the qualitative survey approach (wading and beach walking) were completed at 7 locations along the Cooper River near Camden, New Jersey, in September, 2013. Shells, but no live specimens, were found at 5 of the 7 sites. The presence of shells alone was not considered evidence of live mussels because old shells can erode from riverbanks or wash in from upstream.

Two species of freshwater mussels were recorded in qualitative surveys (Fig. 20), including *Pyganodon cataracta* and *Anodonta implicata*. The alewife floater, *A. implicate*, was more often. More than 18 person hours were spent searching for mussels in the field in September, 2013.

![Figure 20. Table of beach walks and wading at 7 sites along the Cooper river. Shells were found at 5 of the locations. No live animals were found.](image)

<table>
<thead>
<tr>
<th>Site Code</th>
<th>Taxa</th>
<th>Valves</th>
<th>Whole Valves</th>
<th>Fresh Dead</th>
<th>Live</th>
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<td>3</td>
<td></td>
<td></td>
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<tr>
<td>NJ Cooper River 4</td>
<td>Anodonta implicata</td>
<td>5</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NJ Cooper River 5</td>
<td>Anodonta implicata</td>
<td>2</td>
<td>1</td>
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<td>NJ Cooper River 7</td>
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<td></td>
<td></td>
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<tr>
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<td>Pyganodon cataracta</td>
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<tr>
<td>NJ Cooper River 10</td>
<td>N/A</td>
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</tr>
</tbody>
</table>

Additional mussel survey data were collected for the Cooper River using funding from other sources. On July 15, 2013, for example, 23 participants from the Rutgers Cooperative Extension of Burlington and Camden counties, joined PDE staff, Dr. Danielle Kreeger and Dee Ross, for a morning of freshwater mussel education (Fig. 21) followed by in-stream mussel survey training in the afternoon (Fig. 22). Topics covered in the classroom portion of the workshop included:

- What are mussels?
- Lifecycle of freshwater mussels
- Why are mussels so important?
- Why do we need volunteers?
- What is this information being used for?
- Information Datasheets – how to fill them out and upload information to PDE
• What if there are no mussels to be found?
• Safety
• *Freshwater Mussels of the Delaware Estuary* guidebook
• Surveys
• Assessment
• Conservation
• Reintroduction
• Propagation
• Habitat Restoration
• Research & Monitoring
• Outreach

Participants surveyed at least 500 feet of the river, and three species of freshwater mussels were found: *Elliptio complanta*, *Pyganodon cataracta*, and *Anodonta implicata*. Participants were also taught how to record information on the provided/downloadable datasheets, and how to use the online web portal to upload the information so that they could continue to look for mussels in their local streams and share their findings with PDE scientists. For more information on this successful outreach program, please see: http://delawareestuary.org/mussel-survey-program.

**Estimate of Mussel-Mediated Water Quality Benefits**

Despite their relatively lower densities and body mass at the Harrison site compared to other areas, the mussel population is still estimated to make a substantial contribution to the maintenance of water quality. Extrapolating our estimated mussel demographics data to the total estimated bottom area within the four zones, it is estimated that there are 52,368 freshwater mussels living along the Harrison Landfill shoreline.
The collective dry tissue mass of these is estimated to be about 207 kg. The standard clearance rate of 0.875 L h\(^{-1}\) g DTW\(^{-1}\) (see methods for calculations and assumptions) was applied to estimates of mussel dry tissue weight per study site to predict their collective water clearance rates in gallons per hour per total dry tissue weight at each site (English units are shown for easy comparison to local flow rates and drinking water intake rates). Their combined clearance rates are estimated to be more than a million gallons of water per day (MGD), meaning that they process that volume through their filter-feeding gills. At a typical concentration of 10 mg per liter for (dry) total suspended solids (TSS, base flow conditions), this clearance would equate to the removal of about 15.9 metric tons of dry TSS per year (Table 5).

One of the main reasons for the low mussel abundance at the Harrison Landfill site could in fact be suboptimal current bottom substrates. Our past surveys upstream indicated that both mussel density and richness were greater in areas with stable, courser grained substrates (Kreeger et al. 2013). At the Harrison Landfill site, all surveyed locations had substrates varying from clay to silt with virtually no course grained material (sand, pebbles, pea gravel). Mussels were often aggregated around course woody debris (e.g., large tree limbs, trees) that had washed into the site, presumably offering some stability to the bottom.

<table>
<thead>
<tr>
<th>Site</th>
<th>Zone</th>
<th>Approximate Zone Area (m(^2))</th>
<th>Estimated Total Mussel Number</th>
<th>Estimated Mussel Tissue Dry Weight (g)</th>
<th>Typical Clearance Rate (L hr(^{-1}) g DTW(^{-1}))</th>
<th>Typical Clearance Rate (gal day(^{-1}) g DTW(^{-1}))</th>
<th>Bed Clearance Rate (gal day(^{-1}))</th>
<th>Typical TSS Filtration (kg DW year(^{-1}))</th>
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<td><strong>Total</strong></td>
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<td>52,368</td>
<td>206,554</td>
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There also was little coverage of submerged aquatic vegetation (SAV), which also suggests that the bottom is highly dynamic with high bed transport rates. The Confluence and Delaware River search zones had the greatest SAV coverage, but it was not robust at any location. Freshwater mussel and SAV...
density tends to be positively associated in the tidal Delaware River (Kreeger et al. 2013), possibly reflecting a mutualistic beneficial ecological association where they co-occur.

If freshwater mussel habitat was incorporated into the design of a living shoreline project at the Harrison Landfill site, there is potential to significantly increase mussel population density and associated benefits for water quality. Since the Harrison site appears to have very unstable bottom conditions, one goal of a hybrid mosaic living shoreline design could be to stabilize bottom conditions where mussels exist and promote courser substrates that mussels and SAV prefer. As noted above, boosting overall mussels is also likely to benefit rare and sensitive mussel taxa since we have found previously that rare species are most abundant within large beds of more common species.

To demonstrate the potential water quality benefits of mussel habitat enhancement, it is interesting to compare the estimated water processing potential of existing mussels at the Harrison shoreline site with the potential future uplift in water processing capacity if the mussel population would become comparable to nearby beds that have been surveyed (Kreeger et al. 2013). Of the beds surveyed earlier, the lowest mussel densities and biomass were at “Site A” and the greatest were at “Site B.” If mussel populations at the Harrison Landfill shoreline were enhanced to be comparable to Site A (Scenario A), mussel densities would be increased from 1.2 to 5.5 per meter square, and mussel dry tissue mass would be increased from 5.1 to 17.5 grams per meter square. Assuming that the total areas within the four Harrison Landfill survey zones (Confluence, Cooper, Mouth, Delaware) could have their habitats enhanced to support these “Site A” mussel densities, then the daily processing of water would increase by from 1.1 million gallons per day (MGD) to 3.3 MGD, representing a service uplift of 2.17 MGD of water processing for Scenario A. The annual TSS removal would rise three-fold to more than 45 metric tons. Since Scenario A is representative of the “low range” for reference mussel densities, it can be considered to be a conservative estimate of service uplift. If the project was exceptionally successful and mussel beds were enhanced to be comparable to our reference conditions at Site B (Scenario B), then the total number of mussels would increase from 52,368 to 1,027,253, a 20-fold increase. The mussels associated with Scenario B would be estimated to filter 14.4 MGD and the TSS removal would be 12.6 times greater than present, 199 metric tons per year.

It is important to emphasize that these estimates are course because they are based on literature data for other species from other areas of the United States, including some laboratory studies that do not simulate natural conditions. Physiological processing of suspended matter by filter-feeding bivalves is highly variable, depending on water temperature (season, metabolic rates), food quantity and quality, and the seasonal variation in nutritional demands associated with alternating cycles of growth and reproduction. To date, funding has not been available to quantify basic physiological rate functions during the year for Delaware River mussel species.

Another caveat is that the uptake of particles by mussels (with associated particle-bound nutrients) does not equate with net removal of the filtered material from the system. Some portion of the filtered material is returned via biodeposits (feces, pseudofeces) and excretory wastes, and these returns also vary seasonally, with physiological status, and possibly also among species. More empirical study is needed to develop quantitative, physiologically-based models for water quality benefits at the organism and population levels.
Finally, at the population and system levels, more study is needed to model the exchange of water parcels with the benthic boundary layer of the river in the vicinity of mussel beds. Although the tidal freshwater zone of the Delaware River is well mixed by the tides, it cannot be assumed that mussels have access to all of the suspended particles which may tend to concentrate in some areas more than others.

The total estimated daily clearance of 1.1 million gallons of water, and annual filtration of 15.8 metric tons of TSS by mussels within current Harrison Landfill shoreline area, is significant. The City of Philadelphia removes approximately 400 million gallons of water per day from the same reach of the Delaware River to supply the region’s drinking water needs, for comparison. We only surveyed 3.4 hectares of suitable habitat. Mussel densities were well below densities measured on mussel beds upstream on the Delaware River. The total current amount of suitable mussel habitat in the river is not known, but is likely to be orders of magnitude higher than what has been surveyed to date. This means that the current mussel stocks in the Delaware River are likely yielding quantitatively relevant services by filtering significant amounts of particulate matter, possibly helping to sustain lower turbidity levels in this reach of the river than what might otherwise exist. Importantly, many areas that have been surveyed have very poor bottom conditions for mussels, often exhibited by soft and unstable substrates due to stormwater and erosion. Hence, restoration of bottom habitats, such as in living shoreline projects, has the potential to enhance the carrying capacity of the system for native mussels, thereby also leading to enhanced benefits for water quality. At the 3.4 hectare Harrison Landfill shoreline site, for example, we estimate that habitat improvements could lead to an increase in mussel numbers from 52,000 to between 187,000-1,027,000 animals, which would boost TSS removal from 1.1 tons/yr to between 3.3-14.4 tons per year. Assuming much of the removed material gets buried on site, removal rates for particulate nutrients would also be enhanced, especially if denitrification was also enhanced.

**Living Shoreline Conceptual Plan**

Rather than one single conceptual plan for a living shoreline at the Harrison Landfill site, the results are shown as a series of four living shoreline options, and with a fifth depiction showing all options together. These conceptual designs are meant as ideas for discussion purposes only. A formal design would require additional site characterization as well as assistance from engineering experts and hydrologists to ensure the greatest bottom stability, trapping of course grained substrates, and wave attenuation.

The various options are organized by habitat feature:

- Baseline site conditions (i.e., no action)
- Low marsh elevation/stabilization
- High marsh islands
- High marsh/upland grading
- Shallow subtidal mussel/SAV

**Baseline Site Conditions:** The current characteristics of the Harrison Landfill shoreline are described above (see Site Reconnaissance) and visually summarized in Figures 23 and 24. The purpose of these figures is to provide the reader with a visual sense of baseline conditions in the same format that the living shoreline conceptual designs will be presented.
Figure 23. Overhead view of baseline conditions at the Harrison Landfill shoreline in North...
Figure 24. Profile view of baseline conditions at the Harrison Landfill shoreline in North Camden, New Jersey.
Figure 25. Overhead view of created low marsh habitat at the Harrison Landfill shoreline in North Camden, New Jersey.
Figure 26. Profile view of created low marsh habitat at the Harrison Landfill shoreline in North Camden, New Jersey.
High Marsh Islands (Figs. 27, 28): Within the area slated for low marsh habitat, a two-tiered coir fiber log ovals can be constructed to increase the existing elevation to approximately 0.3 meters below MHW. This will create pockets of sediment elevated above low marsh habitat at an optimum growth elevation for high marsh species such as *Zizania* (wild rice) and *Typha* (cat tail). The integration of high marsh habitat into the low marsh area will create a complex topographic mosaic along the mudflat, increasing habitat complexity, species diversity, and ecological productivity.

![Figure 27. Overhead view of created high marsh habitat at the Harrison Landfill shoreline in North Camden, New Jersey.](image)
Figure 28. Profile view of high marsh habitat at the Harrison Landfill shoreline in North Camden, New Jersey.
High Marsh/ Upland Grading (Figs. 29, 30): In order to build habitat complexity and connectivity, the steep rocky gradient in the northeast section of the site can be regraded to bridge high marsh habitat with the steeper slope leading to the landfill area. Native species such as *Zizania* (wild rice) and *Typha* (cat tail) have an optimum lower growth threshold at 0.5m below MHW. To properly accommodate this threshold, the waterward portion of the regraded area should be no lower than 0.3m in order to ensure optimum high marsh plant productivity. Moving landward, the regraded area will increase in elevation to MHHW, the upper threshold for these high marsh populations, at which point the slope will gradually increase to meet the slope of the landfill. In this area a variety of upland and scrub brush could be planted.

![Diagram of created high marsh and regraded slope habitat](image)

**Figure 29.** Overhead view of created high marsh and regraded slope habitat at the Harrison Landfill shoreline in North Camden, New Jersey
Figure 30. Profile view of created high marsh and regraded slope habitat at the Harrison Landfill shoreline in North Camden, New Jersey
**Shallow Subtidal Mussel/SAV Habitat** (Figs. 31, 32): Since freshwater mussels have been located in the Delaware and Cooper Rivers near the Harrison Avenue Landfill site, it is possible to enhance mussel habitat by expanding the proper substrate and conditions needed for sustainable populations along the site. Optimum freshwater mussel habitat requires substrate stability. Suitable substrate, such as gravel and cobble, as well as silty mud, can be highly affected by currents and shear stress along the benthic/water column interface. In order to insure the long term stability of the benthic habitat, the proper energetic conditions must be provided. In order to provide these conditions, salvaged natural materials salvaged from the upper portion of the site such as trees, drift wood and rock can be placed in configurations to dampen the water flow. If additional materials are required, constructed materials such as oyster castes or wave attenuation devices (WADs) can be used in tandem with the salvaged items. The resulting lower energy refugia would be expected to provide suitable habitat for adult freshwater mussels, and to recruit juveniles over time. As freshwater mussels are associated with the emergence of submerged aquatic vegetation (SAV) due to water clarity enhancement by the bivalves, SAV bed growth would also be expected to increase.

![Figure 31. Overhead view of created freshwater mussel and SAV habitat at the Harrison Landfill shoreline in North Camden, New Jersey.](image-url)
Figure 32. Profile view of created freshwater mussel and SAV habitat at the Harrison Landfill shoreline in North Camden, New Jersey.
Complete Habitat Mosaic (Fig. 33): This conceptual design incorporates all four individual habitat concepts into a complex, diverse habitat mosaic. This full suite of activities is the preferred option as it would yield the most structural complexity, resilience and biodiversity. Based on the reconnaissance data highlighting the large open expanse of mudflat available, we recommend the complete habitat mosaic approach, where the synergistic uplift provided by a variety of habitats would be more resilient and productive than any habitat functioning in isolation. Furthermore, the mosaic approach would allow for increased ecological complexity, by providing habitat for a diverse array of flora and faunal species, increasing the richness and interactive feedback capabilities of the area.

Figure 33. Overhead view of the complete habitat mosaic at the Harrison Landfill shoreline in North Camden, New Jersey.
Dissemination of Results

Our efforts in Camden over the past year have included involvement in the Camden Urban Waters Working Group, the Urban Waters Federal Partnership, and the Camden Collaborative Initiative. We also participated and provided a display at the Camden Stormwater Management and Resource Training (SMART) annual conference. PDE involvement in all of these efforts were to develop a better understanding of Camden’s challenges and needs, as well as developing better relationships with Camden’s environmental community and area stakeholders. By and large, our work with stakeholder groups in Camden has revealed that flooding concerns and resulting contamination are of great concern. We found considerable interest in the idea to pair solutions for these concerns with any type of ecological uplift in the area.

The Camden Urban Waters Working Group is an informal coalition of environmental organizations working in Camden, and was established in May 2012 by the New Jersey Academy of Aquatic Sciences. After the initial meeting, PDE became the convener. The purpose of the working group is to foster communication among environmental organizations working in Camden, to ensure that we are working alongside one another (and not duplicating or hindering efforts already underway), and to better share resources. During these meetings, we share current projects and initiatives, talk about where we can plug into one another’s work, and try to envision the next steps for the environmental community in Camden. The group’s next meeting will be held on Wednesday, July 9th from 1:00-3:00 at the Camden County Municipal Utility Authority (CCMUA).

The Camden Collaborative Initiative (CCI) is a formalized initiative composed of topic-driven task forces in the city of Camden that began in March 2013. The CCI is spearheaded by the CCMUA and Cooper’s Ferry Partnership. The CCI currently has six task forces on flooding, brownfields, air pollution, environmental justice, environmental education, and recycling. PDE is involved with the brownfields task force and the environmental education task force. Additionally, we took part in the annual conference of the group that runs the flooding task force—Camden SMART. At the conference, we focused our efforts on raising awareness about living shorelines and the benefits of restoring mussel populations in the urban waterways.

The Urban Waters Federal Partnership is an initiative that endeavors to harness the collective power of a number of different federal agencies in order to help certain regions to revitalize urban waterways and improve quality of life. The Delaware River Watershed was selected as a site for the Urban Waters Federal Partnership, and the initiative includes a focus on Camden, as well as Philadelphia, Chester, and Wilmington. PDE has been involved with this process and continues to ensure that the process is linked to other ongoing regional efforts.

In the future, PDE will continue to participate in these groups, and will rely on partners in these groups (particularly the Working Group and the CCI) to procure input for our potential future work and projects within Camden. We’re excited to be a part of the environmental and social momentum that has been gathering in the City, and we hope to be a part of the solution to issues with flooding and contamination in order to benefit local human and non-human communities.
Next Steps

The following activities are recommended to build on the results of this study and work toward a more
resilient, healthier, and ecologically enhanced urban waterfront area in Camden, New Jersey.

1. Share the conceptual designs for various living shoreline options with local and state decision
   makers, and then modify the designs to address appropriate concerns or suggestions.
2. Engage engineering and hydrodynamic experts to develop formal site plans for the selected living
   shoreline option.
3. Develop an implementation plan that would be most cost effective while also protecting
   ecologically significant existing biota.
4. Develop a monitoring plan for living shoreline performance that follows the Before-After-
   Control-Impact statistical design, with suitable reference locations for additional comparison.
5. Fill vital data gaps regarding the water quality benefits of target biota that would be foundational
   species in the living shoreline design, such as species-specific physiological rate functions of
   native freshwater mussel species and possibly also submerged aquatic vegetation and vascular
   plants.
6. Secure funding for a living shoreline project that addresses both water quality and ecological
   enhancement goals.
7. Proceed with permitting, monitoring, and then implementation.
8. Develop an outreach plan, especially targeting local communities.
9. Continue communications with local and regional decision makers throughout #1-8 to ensure that
   any on-the-ground activities are responsive to local needs, while also addressing watershed-wide
   conservation and restoration priorities.

Literature Cited

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