Freshwater Mussel Community Composition and Relative Abundance in the Lower Delaware River

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Executive Summary

Freshwater mussels are one of the most imperiled organisms worldwide and provide a variety of important functions in the streams and rivers they inhabit. The Delaware River, USA is a stronghold for freshwater mussel diversity and biomass, both of which have been documented for the upper reaches (Upper Delaware Scenic and Recreational River) and the middle reaches (Middle Delaware Scenic and Recreational River, including the Delaware Watergap National Recreational Area). However, limited data are available on the freshwater mussel fauna in the lower non-tidal river (which includes the Lower Delaware Wild and Scenic River). We completed semi-quantitative snorkel surveys and supplemental point surveys in the 75 miles of the Lower Delaware River between Portland-Columbia (PA/NJ) to the head of tide at Trenton, NJ. We counted a total of 25,532 mussels comprising seven species. The three most common species included *Elliptio complanata* (94.4% of total individuals), *Lampsilis cariosa* (3.3%), and *Anodonta implicata* (1.4%) with *Pyganodon cataracta*, *Strophitus undulatus*, *Alasmidonta undulata*, and *Leptodea ochracea* comprising the final 0.8% of mussels found. Significant changes in mussel catch per unit effort (CPUE) were detected below the confluence of the historically polluted Lehigh River, with significant declines in *E. complanata* CPUE and significant increases in *L. cariosa* CPUE (although increases were not great enough to compensate for *E. complanata* loss). Patterns in mussel distribution around the Lehigh confluence matched chemical signatures of Lehigh water input. Specifically, *E. complanata* declined abruptly along the Pennsylvania bank of the river where Lehigh water (and the presumptive stressor or stressors) was more concentrated. Along the New Jersey bank, where the Lehigh River more gradually mixed with the Delaware River water, the declines in *E. complanata* occurred gradually over many river segments rather than immediately at the confluence. The causes of the dramatic shifts in mussel community composition remain to be investigated along with the ecological consequences of depleted mussel biomass in the Lower Delaware River below the Lehigh River.

Introduction

North American lakes and rivers are home to the largest diversity of freshwater mussels (Bivalvia, Unionoida) in the world. These organisms are beneficial to the systems they inhabit through activities such as filtration, biodeposition, and nutrient cycling (Spooner and Vaughn 2006, Vaughn 2010). Mussels, however, are a highly imperiled group of freshwater organisms, exhibiting declines worldwide (Lydeard et al. 2004). Due to both their ecological importance and their current status, mussel conservation has become a priority for many state and federal agencies. Successful mussel preservation, however, relies on a comprehensive understanding of their basic distributions and life histories, data that are lacking for many mussel populations.

The Delaware River is a stronghold for Atlantic-slope mussel diversity and biomass. Lellis (2001, 2002) conducted comprehensive semi-quantitative surveys of the Upper Delaware Scenic and Recreational River in 2000 and subsequently the Delaware Watergap National Recreation Area in 2001, supplementing the semi-quantitative surveys with intensive quantitative surveys. These surveys yielded a complete survey of the entire Delaware River from Hancock, NY (River Mile[1] [RM] 331), down into the Lower Delaware Scenic and Recreational River at Portland-Columbia (RM 208). A total of nine species of freshwater mussels were found. The common Eastern Elliptio (*Elliptio complanata*) comprised the majority of mussels in the upper and middle Delaware (>98%), but rare species were also found, including populations of the federally endangered Dwarf Wedgemussel (*Alasmidonta heterodon*), the NJ state endangered Brook Floater (*Alasmidonta varicosa*), and the NJ state threatened Yellow Lampmussel (*Lampsilis cariosa*). Emerging data from surveys in the tidal Delaware River (Kreeger et al. 2011) have expanded the Delaware River species list from 9 to

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[1] The Delaware River mileage system is explained on the DRBC website (www.nj.gov/drbc/basin/river/); overall, miles are from the Atlantic Ocean so increasing numbers are further upstream.

11, adding the Eastern Pondmussel (*Ligumia nasuta*) and the Tidewater Mucket (*Leptodea ochracea*) as species retaining apparently robust populations within the mainstem Delaware River. Furthermore, sparse records indicate that the Eastern Lampmussel (*Lampsilis radiata*) may retain small populations within the non-tidal Delaware River, increasing the known fauna to 12 species, thus encompassing nearly the entire complement of the northern Atlantic-slope mussel diversity.

Much less is known about the mussel fauna of the Lower Delaware River below the Delaware Watergap and above the head-of-tide at Trenton, NJ. Most of the mussel species expected in the lower Delaware have been documented (see Normandeau 2010, 2011a, 2011b), yet the full species diversity and their distribution are not known. Additionally, some of the earliest documentations of the federally endangered Dwarf Wedgemussel (*A. heterodon*) occurred in the lower Delaware River basin, suggesting the potential for undocumented populations (Moser 1993). Equally important is whether the freshwater mussel fauna reflects the current and historic changes in water quality within the Lower Delaware.

The largest tributary to the non-tidal Delaware River is the Lehigh River (~1360 mi^2 drainage area; drainage area of the Delaware above this confluence is approximately 4720 mi^2). Historically, the Lehigh River was severely polluted (containing twelve Superfund sites within its watershed) and had major impacts on resident aquatic species (Pollison and Craighead 1968, PAFBC 2007 and references therein). Today, the Lehigh confluence continues to serve as an important change-point for water quality, with elevated nutrients (and possibly other contaminants) found in the Delaware mainstem below this confluence (DRBC 2010). Although modest changes to the benthic macroinvertebrate community have been documented for the Delaware River below the Lehigh confluence (Silldorff and Limbeck 2009), the extent of the aquatic community changes at the Lehigh have been poorly evaluated, particularly for groups such as freshwater mussels. Indeed, recent reports of diverse and abundant populations of freshwater mussels in the tidal Delaware River near Philadelphia (see Kreeger et al. 2011), where gross pollution has only recently been ameliorated (Albert 1998), suggests that the mussel fauna of the Delaware River may persist through moderate to severe changes in certain types of water quality degradation.

In an effort to fill the data gap for mussels in the Lower Delaware River and to evaluate the ecological ramifications of the Lehigh River water quality changes, surveys were conducted between the Portland-Columbia footbridge (River Mile [RM] 208) and the head-of-tide at Trenton, NJ (RM 133) during the summers of 2012 and 2013 (Fig. 1). The objectives of these surveys were threefold: 1) to determine which species of freshwater mussels occurred in the lower Delaware River; 2) to quantify the distribution and relative abundance of these species; and 3) to compare the mussel communities (species composition and relative abundance) above and below the confluence of the Lehigh River.

Methods

Semi-Quantitative Snorkel Surveys

Our study relied primarily on semi-quantitative mask-and-snorkel surveys by teams of scientists that emulated the techniques used for the Upper Delaware and the Delaware Watergap surveys (Lellis 2001, 2002). Our semi-quantitative surveys were all conducted during the summer of 2013. The majority of survey effort centered on twelve (12) randomized reaches selected in a point-transect fashion to spread the survey effort throughout the entire length of the Lower Delaware River (Fig. 1). Initial randomized starting points were first selected near the upper limit of the survey area (RM208) and near the end of the Lehigh River intensive surveys (see below). Reaches were then designated beginning every 5.7 miles below these two randomized starting points, with four (4) reaches delineated above the Lehigh confluence and eight (8) reaches below the confluence. The randomized reaches were supplemented by three targeted and intensive survey reaches that continuously covered the Lehigh River confluence with the Delaware, beginning 2.5 miles above the Lehigh and extending 3.7 miles below the confluence. Finally, one additional reach (Reach 4x) was added post hoc during the 2013 season to more carefully evaluate unusual patterns in mussels abundance near the Martins Creek tributary confluence (RM190.5). In an effort to minimize systematic survey bias through time, the 12 randomized survey reaches were sampled by alternating between surveys below the Lehigh confluence and above the Lehigh confluence on successive survey days in a haphazard manner so that position downstream along the river was not associated with time or date of survey. Only the three Lehigh confluence reaches were surveyed successively in an upstream-to-downstream direction, as was necessary to provide continuous coverage of the river in this section.

Within each reach, surveys proceeded from upstream to downstream in successive "segments" of approximately 200 meters in length, comparable to the methods of Lellis (2001, 2002). These semi-quantitative surveys consisted of intensive snorkel surveys by a 5-7 person team working in two tandem groups, one on each side of the river (or island, if relevant). When team size permitted, one member was relegated to the boat to mark segments, record data, and collect stream parameters (including GPS data, temperature, conductivity, and habitat notes). Remaining team members were split between PA and NJ banks and visually searched sections using snorkel gear. Individuals were spread out from the shores at even intervals, depending on segment depth and velocity, into three positions (two when crew was limited) to survey individual lanes. In general, these lanes were snorkeled from the upstream to the downstream border of each segment within a narrow band of depth and distance from shore, but unique habitats, channels, and eddies were also investigated. Individuals searched each segment for roughly 15 minutes, although total survey time and segment length varied depending on the number of surveyors and complexity of habitat. While position #1 (nearest to bank) focused in mostly shallow areas near shore, positions #2 and 3 increasingly required diving, with a maximum depth of ~15 feet surveyed. Survey crew members regularly rotated positions during the survey so that individual lanes would not be associated throughout a reach with a single surveyor, and the two groups surveying each side of the river would switch to the opposite side of the river roughly mid-day (NJ to PA and PA to NJ).

Individual mussels were removed from the sediment when necessary, identified to species level, and returned to their original location. Any questionable mussels were brought to the surface for group consensus before identification. Surveyors reported individual species counts at the end of each segment. Because of logistics, variable sampling conditions, and weather constraints, distances surveyed differed among reaches, with the shortest reach surveyed at 1.4 miles and the longest at 2.7 miles (Table 1, Fig. 1). When islands were present, the best course of surveying was determined based on logistics, potential for finding mussel populations, and field work safety.

Supplemental Point Surveys

Due to limitations in time and funding, we were unable to complete semi-quantitative surveys over the entire 75 miles of the Lower Delaware River. However, additional supplemental point surveys were conducted throughout the Lower Delaware River in 2012 and 2013, focusing on areas not covered in the semi-quantitative survey (Fig. 1). For all point surveys, restricted areas were surveyed via mask-and-snorkel and the total survey time was recorded in an effort to provide comparable estimates of mussel catch rates.

During 2012, initial point surveys were completed as part of the scoping efforts for the project. During 2013, more extensive point surveys were conducted as part of "float-overs" for large river reaches, with one or two teams deploying at field-selected sites along both banks of the river for a series of point surveys. These 2013 supplemental point surveys covered nearly the entire length of the 75 miles of this study, beginning at the Portland-Columbia footbridge (RM208) and extending down to the Point Pleasant pool above the wing dam (RM156), with the lower 23 miles of river omitted because of time constraints and difficult flow and visibility conditions during the summer of 2013. Because of the difficulties in securing enough survey days due to both high water and poor visibility in 2013, a decision was made to prioritize the semi-quantitative surveys ahead of these point surveys (note: some monthly rainfall records were broken during the summer of 2013).

Delineation of Lehigh Mixing Zone

The mixing of two rivers at their confluence occurs gradually through a "mixing zone" that depends on specific features of the rivers and the river channel. For the Delaware and Lehigh confluence (RM 183.7), no quantitative assessment of this mixing zone has been performed or modeled. Because of the strong differences in water quality between these two rivers (see DRBC 2010) and the expected gradient in water quality in the mixing zone below their confluence, we conducted an initial quantitative survey of this mixing zone in August 2013.

Among the differences in water quality parameters between the Delaware and Lehigh Rivers, specific conductance of the Lehigh River typically approaches or exceeds 200% of the specific conductance in the Delaware River immediately upstream from their confluence (DRBC 2010). As a conservative water quality parameter largely unaffected by internal biological activity, specific conductance therefore serves as an excellent inert marker or "tracer" of the differential mixing of the two water sources.

On August 15, 2013, surface measurements of specific conductance were collected at five (5) positions across the Delaware River channel for twenty (20) stations above and below the Lehigh confluence. At each transect, measurements were taken near both the Pennsylvania and New Jersey shore, and then at three positions roughly evenly spaced across the river channel (positions were recorded using a handheld GPS). Both specific conductance and water temperature were measured at each position using a YSI 30 meter (YSI Inc., Yellow Springs, Ohio).

Data Analysis

For each river reach, mussel counts (summed across all surveyors and banks) were standardized to a catch per unit effort (CPUE) corresponding to the number of mussels found in 1 hour of active mussel search time. For parametric statistical analysis, all data were ln+1 transformed prior to analyses to meet assumptions of normality and equal variance and all tests were completed using IBM SPSS Statistics 20 and confirmed using the R statistical package. One-way analysis of variance (ANOVA) was used with reach as the unit of replication to compare mussel CPUE for individual species above and below the Lehigh River using data from only the 12 randomly selected reaches (not including the target reaches above and below the Lehigh as these were not randomly selected). This was done for the three most abundant species found in the survey who each contributed at least 1% of total mussel abundance (*E. complanata*, *L. cariosa*, and *A. implicata*).

Results

Semi-Quantitative Snorkel Surveys

A total of 25,532 mussels were counted during nearly 360 survey hours across 33.3 miles of the Lower Delaware River resulting in a total CPUE of 71 mussels per hour (Tables 1 and 2). Seven species of freshwater mussels were identified. The most abundant species was *Elliptio complanata* (94.4% of total individuals), followed by *Lampsilis cariosa* (3.3%), and *Anodonta implicata* (1.4%). *Pyganodon cataracta*, *Strophitus undulatus*, *Alasmidonta undulata*, and *Leptodea ochracea* made up the final 0.8% of mussels found.

Statistical tests on the distribution of the three common mussels revealed marked shifts in the absolute and relative abundance of mussels in the Lower Delaware River. Most importantly, the dominant Delaware River mussel, *E. complanata*, declined significantly below the Lehigh River ($F_{(1,10)}$=21.9, p=0.001; Fig. 2 and 3). For the 12 randomized survey reaches, *E. complanata* CPUE above the Lehigh averaged 179 individuals per hour while below the Lehigh CPUE averaged 21 individuals per hour, an 8-fold difference. A similar pattern was observed when including all reaches (randomized and non-randomized): CPUE above the Lehigh averaged 152 individuals per hour and below the Lehigh averaged 23 individuals per hour (nearly a 7-fold difference). Looking at each segment within reaches separately and examining the distribution of *E.complanata* CPUE above versus below the Lehigh across all reaches (see Table 3), the median CPUE above the Lehigh was 60 individuals per hour while below the Lehigh the median CPUE was 7 individuals per hour (a 9-fold difference). Together, the survey results show that the dominant mussel in the Delaware River declined between 80% and 90% (5 to 10-fold) below the Lehigh confluence, with the range of the decline depending on the specific statistical measure chosen (see below and *Discussion* for additional details on complexities within this overall pattern).

The results for the second most common mussel in our surveys, *L. cariosa*, were nearly opposite those from *E. complanata*, with significant increases in CPUE for the randomly selected segments below the Lehigh ($F_{(1,10)}$=8.9, p=0.014; Table 2, Fig. 2 and 3). *L. cariosa* was rarely found above the Lehigh (Table 1) but became increasingly common below the Lehigh confluence, peaking at 456 individuals (Reach 11) 10 miles above the head-of-tide at Trenton, NJ (Table 1, Fig. 2; see also Appendix 1). It is important to note, however, the magnitude of *L.cariosa* CPUE (Table 2, Fig. 2 and 3) relative to the dominant *E. complanata*: the highest *L. cariosa* CPUE was only slightly higher than the lowest *E. complanata* CPUE. Similarly, *L. cariosa*'s maximum CPUE was over 10 times lower than the maximum CPUE for *E. complanata*. Thus, the increase in *L. cariosa* below the Lehigh did not compensate for the overall decline in mussel densities, with average CPUE for all mussels below the Lehigh confluence (average of 27 individuals per hour) still remaining 5-fold lower than above the Lehigh (155 individuals per hour).

The patterns for the third most common mussel, *A. implicata*, reveal added complexity compared to the overall patterns for both *E. complanata* and *L. cariosa*. Overall, no statistical difference was found for *A. implicata* when comparing CPUE above the Lehigh to CPUE below the Lehigh for the 12 randomized reaches ($F_{(1,10)}$=2.8, p=0.126). Despite non-significance, *A. implicata* CPUE for the reaches above the Lehigh ranged from 0.4 to 2.8 individuals per hour, but remained consistently low (0.2-0.3 individuals per hour) immediately below the Lehigh confluence (Table 2, Fig. 2 and 3; see also Appendix 1). Some recovery in *A. implicata* CPUE was noted in the most downstream survey reaches. In the final 4 reaches of the Lower Delaware, moderate numbers of *A. implicata* (Table 1) were found, with the CPUE in these reaches varying in a manner consistent with the variation seen above the Lehigh confluence (Table 2, Fig. 2 and 3, Appendix 1).

We encountered four additional mussel species during our 2013 surveys of the Lower Delaware. For *P. cataracta*, little or no pattern was evident in the abundance and distribution of this moderately common mussel species. In addition, field identification of *P. cataracta* (particularly juveniles) was problematic and we feel our counts for *P. cataracta* are preliminary estimates at this time. Sacrificial sampling of *P. cataracta* would be required for more precise and reliable description of the distribution and relative abundance of this mussel. Among the final three species (*L. ochracea, S. undulatus*, *A. undulata*), only a handful of individuals of each were encountered and little can be discerned from such sparse numbers. For *L. ochracea* (tidewater mucket), however, the documentation of this species above the head-of-tide is noteworthy, and the collection of this mussel in the last of the 16 reaches surveyed is consistent with the general distribution of this species in or near freshwater tidal estuaries (Haag 2012).

Finally, we documented finer scale patterns in the *E. complanata* data that merit description. Raw counts (Table 1) and standardized CPUE (Tables 2 and 3, Fig. 2 and 3) were not uniformly high above the Lehigh River. In particular, counts and CPUE were low in the randomly-selected Reach 4, substantially lower than for other random segments above the Lehigh. Because surveys for Reach 4 began precisely at the confluence of a slate-bearing tributary (Martins Creek), which altered the substrate within the mainstem Delaware River near the creek's confluence, an additional and contiguous reach (Reach 4x) upstream from the Martins Creek confluence was added late in the 2013 season to evaluate whether the low counts in Reach 4 might be linked to the Martins Creek confluence. Instead, Reach 4x (above this tributary) showed data highly consistent with the data from Reach 4 itself, with low overall abundances and low CPUE for *E. complanata*, in particular. The subsequent downstream reach ("Above Lehigh" reach) showed increased abundances again, comparable to the numbers seen in Reach 1 and Reach 3 (Tables 1 & 2).

Supplemental Point Surveys

The supplemental point surveys identified five of the seven species found in the semi-quantitative snorkel surveys (Table 4). Many point surveys resulted in no mussels encountered, leading to 0 individuals per hour as the minimum CPUE among the segments for each reach. In addition, two relatively weak patterns can be identified, which are further supported by the results from the semi-quantitative surveys (Table 4). First, high density mussel beds (i.e., CPUE > 300 mussels per hour) were encountered in the point surveys immediately upstream from the Lehigh River confluence. Second, freshwater mussels were rare in the point surveys immediately below the Lehigh confluence. These supplemental point surveys did not encounter any additional species of mussels not found in the semi-quantitative surveys. In addition, the results from the point surveys appear more variable than the results from the semi-quantitative surveys. As a result, point survey results did not strongly influence our understanding and interpretation of the mussel patterns in the Delaware River.

Delineation of Lehigh Mixing Zone

During the mixing zone measurements of specific conductance on August 15, 2013, water levels and discharge for both the Lehigh and Delaware Rivers were elevated, but were along the receding limb of the preceding storm's hydrograph (peak flows were on August 11, 2013). Discharge for the Delaware River at Belvidere, NJ (Gage #01446500), averaged 6040 cfs while discharge for the Lehigh River at Glendon, PA (Gage #01454700), averaged 2650 cfs, giving a discharge ratio of roughly 2.3-to-1 (the drainage area ratio is 3.5-to-1). This indicates that the Lehigh River, on a relative basis, was at a higher stage compared to the Delaware and the volume of discharge from the Lehigh on this survey day was higher than typical conditions. Thus, the Lehigh may have mixed further upstream on August 15, 2013, than it does under median conditions (i.e. our measurements of the mixing zone may over-estimate how quickly the Lehigh and Delaware mix compared to typical conditions). Additional surveys at varying absolute and relative flows will be needed to more completely bracket the range of influence of Lehigh water quality on the zone of mixing.

Above the Lehigh confluence, specific conductance of the Delaware River varied across the channel because of tributary and near-bank influences, but the primary body of water had specific conductance readings between 135 and 148 μS/cm (Table 5 and Appendix 2). The Lehigh River at the USGS station at Glendon, PA, (1.9 river miles upstream from the confluence) had specific conductance readings between 250 and 274 μS/cm for August 15, 2013. At the first transect below the Lehigh confluence (RM 183.49), the Delaware River showed a strong gradient of specific conductance, measuring 263 μS/cm near the Pennsylvania shore and 138 μS/cm near the New Jersey shore, indicating nearly pure Lehigh and Delaware River waters, respectively, along the shorelines at the beginning of the mixing zone (Table 5). Moving downstream, the rivers mixed gradually for the first three river miles, with specific conductance measurements of 228 μS/cm and 159 μS/cm near the Pennsylvania and New Jersey shores, respectively, at RM 180.36; this demonstrates a persistence of the two water bodies far below their confluence. Mixing accelerated near and below Whippoorwill Island and Raubs Island, with specific conductance measurements narrowing to within 5 μS/cm across the channel at RM 176.95 (Table 5). At this first transect below Raubs Island, essentially no difference remained in the specific conductance measurements across the channel, indicating complete mixing between the Lehigh River and the Delaware River had been attained in approximately 6.5 river miles on this date and under these conditions.

Discussion

<u>Species Composition of Mussel Fauna</u>

Snorkel surveys of the Lower Delaware River in 2012 and 2013 confirmed the presence of 7 native freshwater mussel species within the 75 miles from the Portland-Columbia footbridge down to the head-of-tide at Trenton. Not surprisingly, given other surveys in the non-tidal and tidal river, the Eastern Elliptio (*E. complanata*) dominated our collections, with *L. cariosa* and *A. implicata* also common and contributing more than 1% of the total relative abundance. Three additional species (*P. cataracta, S. undulatus, A. undulata*), which have been documented from the non-tidal river, were collected in our surveys, although in low numbers. One additional species, the Tidewater Mucket (*L. ochracea*), has been collected from freshwater tidal reaches of the Delaware River in recent years by scientists from the Partnership for the Delaware Estuary, the Academy of Natural Sciences, and others. Extending those discoveries in the tidal reaches, small numbers of *L. ochracea* were also collected in the non-tidal Lower Delaware River in the most downstream reach of our survey.

Two species were not collected during our survey, however, which have been reported previously from these areas of the Lower Delaware River. First, the federally endangered Dwarf Wedgemussel (*A. heterodon*) historically has been found sporadically throughout the Lower Delaware River basin (USFWS 1993). This increasingly rare mussel was not collected in our surveys, although the rapid nature of our survey methodology may not be well-suited for the detection of rare species. Second, the Eastern Lampmussel (*L. radiata*) has at times been collected in the Lower Delaware (including by PADEP during the summer of 2013), but we did not encounter this uncommon species in our surveys.

Patterns in Mussel Populations

Our semi-quantitative survey of the Lower Delaware River during the summer of 2013 revealed a severe decline in mussels associated with the Lehigh River confluence. The dominant mussel in the Delaware River, *E. complanata*, declined 80% to 90% (between 5 and 10 fold) in the surveyed reaches below the Lehigh River compared to the surveyed reaches above the Lehigh confluence. Although one surveyed reach below the Lehigh (Reach 9) showed a CPUE similar to the reaches above the Lehigh confluence, high-density patches of *E. complanata* encountered regularly above the Lehigh were rare or lacking in the reaches below the Lehigh.

More detailed examination of the mussel data in the mixing zone below the Lehigh support the hypothesis that *E. complanata* (and perhaps *A. implicata*) declines were caused by the Lehigh River influence itself. CPUE for *E. complanata* declined immediately in the first segments below the Lehigh confluence, but only on the Pennsylvania bank where the mixing zone measurements demonstrated nearly pure Lehigh River water (Fig. 4). By contrast, the CPUE for *E. complanata* declined in a gradual manner on the New Jersey bank, a pattern that mirrored the gradual mixing of the Lehigh River water over the course of 6.5 miles during our mixing zone surveys. Such a pattern is, of course, just a correlation. Nevertheless, the overall pattern of *E. complanata* decline in the 50 miles below the Lehigh confluence combined with the more fine-scale decline of this mussel within the Lehigh mixing zone are consistent with a direct effect from some aspect of the Lehigh River (e.g., water quality, sediment quality). Indeed, we could identify no credible alternative hypothesis to explain these concordant patterns. In addition, although identification of stressors to *E. complanata* populations would be purely speculative, the distinct transition at the Lehigh confluence, particularly on the Pennsylvania side of the river, does suggest that the stressor (or stressors) is directly impacting *E. complanata* and is not mitigated through some indirect pathway. Such indirect causal pathways would likely lead to more diffuse and less distinct transitions than observed in this study (Table 2; Fig. 3 and 4).

Like *E. complanata*, CPUE for *A. implicata* declined to zero or near-zero on the Pennsylvania bank of the river immediately below the confluence with the Lehigh River, with a more gradual fade to low levels on the New Jersey bank (Fig. 5). Yet unlike *E. complanata*, CPUE for *A. implicata* rebounded in the lower survey reaches to values seen above the Lehigh confluence (Table 1, Fig. 2 and 3, Appendix 1). Because of these more complex patterns below the Lehigh, the contrast between random segments above and below the Lehigh confluence was non-significant for *A.implicata*.

Two possible interpretations are readily apparent for the more persistent declines of *E. complanata* and the possible recovery of *A. implicata* CPUE below the Lehigh confluence. First, *E. complanta* may be more sensitive to whatever stressor is associated with the Lehigh confluence. As a result, both the increased dilution and any amelioration of the stressor(s) would be sufficient to allow recovery of *A. implicata* but the stressors would remain above ecologically significant thresholds for *E. complanata*. The ubiquitous nature of *E. complanata* throughout the Northeast (Haag 2012), however, suggests that this species is hardy and tolerant of a wide range of environmental conditions. Heightened sensitivity to common stressors (as may be present near the Lehigh confluence) would be surprising given this overall distribution pattern for *E.complanata*, especially relative to rarer species such as *A. implicata*.

A second alternative is that life history differences between these two mussel species could have allowed for more rapid recovery of *A. implicata* populations below the Lehigh confluence. Pollution in the Lehigh River was more severe prior to the Clean Water Act restorations that began in the 1970s, with measureable and significant effects of the Lehigh documented historically within the Delaware River (Pollison and Craighead 1968). With upgraded wastewater treatment and a shift away from heavy industry, the Lehigh River water quality has improved over the past 40 years, with attendant recovery in the Delaware River below the Lehigh confluence. Higher growth rates generally observed in Anodontid species (Haag 2012) may have allowed for more rapid recolonization of *A. implicata* populations following water quality improvements below the Lehigh. In contrast, *E. complanata*'s slower growth rate and longer life span would yield a slower recovery, manifesting itself in suppressed counts and populations sizes throughout the Lower Delaware River below the Lehigh confluence. The relatively strong numbers for *E. complanata* in Reach 9 might suggest the beginning of such a slower recovery for this mussel species.

In marked contrast to the patterns for both *E. complanata* and *A. implicata*, the relative abundance for *L. cariosa* showed substantial and steady increases moving downstream through the Lower Delaware River (Table 1). The reason for these increases remains unclear. Consistently increasing *L. cariosa* populations may suggest increased habitat availability for this species as one proceeds downstream. Indeed, longitudinal changes in the physical and chemical conditions along stream and river corridors constitute a central paradigm in stream ecology (Allan 1995), and have been demonstrated in freshwater mussel communities (Haag 2012). Alternatively, the *L. cariosa* increases could involve both direct responses to water quality changes and indirect responses to low densities of other mussel species. Because *L. cariosa* counts above the Lehigh were extremely sparse, no patterns around the Lehigh confluence could be discerned from our surveys. Yet increasing numbers with greater distance from the Lehigh confluence could imply improving water quality conditions more suitable for *L. cariosa* growth and development as one proceeds downstream. Combined with the persistently low *E.*

complanata numbers below the Lehigh confluence, *L. cariosa* may be able to exploit both the improved water quality and the lack of competition from *E. complanata*, increasing its abundance in these lower reaches near the head-of-tide. Finally, patterns of *L. cariosa* abundance may also be a function of high tolerance to historical Lehigh River stressors (and thus minimal impacts on *L. cariosa* population levels). All of these possibilities warrant further investigation to understand patterns in *L. cariosa*'s abundance in the Lower Delaware River.

Freshwater mussels provide a variety of important functions to the ecosystems they inhabit, many of which are biomass dependent and vary according to species (Spooner and Vaughn 2008, Vaughn 2010). Declines in overall mussel biomass and shifts in community composition below the Lehigh River confluence could therefore have consequences for a variety of key ecological processes including nutrient cycling and retention, removal of particulates via biofiltration, and providing habitat for macroinvertebrates and biofilms (Spooner and Vaughn 2006, Spooner et al. 2013, Vaughn 2010). Increases in *L. cariosa* abundance below the Lehigh were not comparable to the loss of *E. complanata* abundance (and biomass). Above the Lehigh, *E. complanata* relative to *L. cariosa* abundance ranged from 200:1 in low-density reaches (Reach 4x) to nearly 7000:1 in high density areas (Reach 2). The ability for *L. cariosa* to functionally compensate for *E. complanata* remains to be determined, but is highly unlikely given the magnitude of services one individual *L. cariosa* would have to provide to counteract the loss of hundreds (or thousands) of *E. complanata*.

Survey Techniques & Consistency with Prior Surveys

Ecologists face many challenges in understanding the threats to freshwater mussel populations and reversing the extensive declines nationwide. Among the most basic challenges is the accurate estimation of mussel population sizes and their variability across the landscape. Mussels are notoriously patchy, and the determinants of within-system patchiness remain poorly understood (Vaughn 1997). As a result, anything short of complete census techniques runs the risk of overlooking important patterns and structure in these mussel populations, both on the high end and the low end of mussel densities.

Previous USGS surveys of the Upper Delaware and Delaware Watergap (Lellis 2001, 2002) pushed the limits of large-river techniques by attempting to survey the entire length of the river with individual survey members spanning the entire width of the river. The resulting data provide a comprehensive picture of the mussels of the Delaware River in these river sections. Indeed, in part because of the intense survey efforts, multiple subpopulations of the federally endangered Dwarf Wedgmussel (*A. heterodon*) were discovered in the upper sections of the Upper Delaware which had never been documented before.

Our surveys of the Lower Delaware River continued to highlight the incredible variability in mussel densities within spatially contiguous sections of the river. Within the limits of a single survey reach (typically 1 to 3 miles long), the CPUE of the three most common species in our surveys spanned between two and three orders of magnitude, and both no-mussel-segments and segments approaching 1000 mussels per hour were encountered in the same reach (Table 3 and Appendix 1). Thus, it was not unusual for our team of surveyors to encounter a high-density segment after numerous segments of low densities or even an absence of mussels, and the locations of both high-density and low-density patches could not be reliably anticipated.

In an effort to document the important patterns in mussel variation of the Lower Delaware River, our survey techniques closely emulated those of the semi-quantitative surveys for the Upper Delaware River and the Delaware Watergap National Recreation Areas (Lellis

2001, 2002). Two substantive differences, however, could limit the comparability of our data with those prior surveys. First, the earlier surveys used larger crews that spanned the entire width of the river and did not focus solely on bands parallel to the shoreline. Discussions with members of those earlier surveys suggested that no new mussel species were found in deep water habitat compared to near shore habitat. Our decision to omit mid-channel positions during the survey was made due to time and funding limitations associated with hiring additional surveyors (to span the entire river) and contracting SCUBA services.

The second difference in survey techniques was the complete coverage from upstream to downstream that was accomplished with the earlier Upper Delaware and Delaware Watergap surveys, while our surveys relied primarily on randomized starting positions and incomplete coverage to estimate the dominant patterns in absolute and relative abundance. More complete coverage of the entire river, particularly given the patchy nature of mussel populations, would clearly provide greater confidence that a particular survey captures the patterns in distribution and abundance. Yet resources for these mussel surveys are typically quite limited. Our survey methodology attempted to obtain comparable data to the earlier full surveys under the time and financial constraints for our project.

A cursory comparison between survey results by Lellis (2002) in the Delaware Watergap and our Lower Delaware River survey shows a high degree of consistency in CPUE results, and in the patterns of CPUE variation, for *E. complanata* and *A. implicata*, even though the surveys were separated by over 10 years (Fig. 6). For example, near the transition from the Delaware Watergap survey to the Lower Delaware survey (near RM 210), the maximum CPUE and the range of CPUEs seen in the two surveys are quite similar for both species. For future surveys, these comparable results could help guide the allocation of time and resources. The decision to forego survey positions ranging throughout the center of the channel did not appear to cause a major shift in our estimate of relative abundance for these two common species. In addition, the ability of our Lower Delaware survey to apparently capture the main patterns in mussel populations is encouraging; future survey efforts that are spatially extensive, but that do not cover the entire river, may provide adequate data on mussel distribution.

Nonetheless, there is merit to investing in spatially extensive surveys as demonstrated from our Lower Delaware mussel survey. We found high levels of patchiness among reaches and among segments, and at times found substantial differences in mussel abundance even within segments. Such patchiness suggests that point surveys (like our supplemental surveys) and surveys with limited spatial extent run the risk of over- or underestimating mussel CPUE and not detecting rare species inhabiting localized areas within the river (e.g., *A. undulata* in our survey). Survey techniques that can help understand not just central tendencies, such as mean population sizes, but which also describe the range of conditions and patterns of variability provide a richer, more complete picture of freshwater mussel populations.

Future Study Needs

Patterns in distribution and abundance of freshwater mussels in the Delaware River warrant further investigation. Specifically, more current surveys of selected reaches in the Upper Delaware Scenic Recreation Area and the Delaware Watergap are necessary. These resurvey efforts would allow us to document changes in mussel communities that may have occurred over the last 14+ years. Doing so would also allow for a more accurate comparison of the upper and middle Delaware River survey results to data collected from the Lower Delaware River. Quantitative surveys in the Lower Delaware River would also allow us to estimate mussel population sizes for comparison to population estimates found in the upper and middle reaches of the river. Further semi-quantitative surveys in select high-diversity reaches or unsurveyed areas of the Lower Delaware River may detect rare species that have historically been documented but were not found in our surveys (e.g., Dwarf wedgemussel, *A. heterodon*; Eastern Lampmussel, *L. radiata*).

A detailed examination of the ecological implications for *E. complanata* decline and *L. cariosa* increase below the Lehigh River are also necessary. Understanding the mechanisms of *E. complanata* decline below the Lehigh could facilitate recovery of this species and these associated ecosystem functions. Candidate stressors, including heavy metals and interstitial ammonia, should be investigated in both a field (transplant studies) and laboratory setting for all freshwater mussel life stages. Quantitative surveys for juvenile *E. complanata* (and *A. implicata*) below the Lehigh are also necessary to determine if populations are beginning to recolonize. Such surveys in conjunction with water quality data may provide insight into water quality thresholds necessary for re-establishing mussel populations in the Lower Delaware.

Acknowledgements

This effort benefitted greatly from the information and assistance provided by Jeff Cole. We also wish to thank Bill Lellis for his guidance and support, as well as Jessica Newbern and Julie Bell. Funding for this research was provided by both the National Park Service and the U.S. Environmental Protection Agency to the Delaware River Basin Commission. The research was conducted under permits PA #467 (Scientific Collector Permit and Chapter 75.4 Special Permit for the Collection of Threatened and Endangered Species) and NJ #SC2013153 (Scientific Collecting Permit).

Figure 1. Map of Lower Delaware River showing locations of semi-quantitative snorkel reaches (size of circle proportional to length of surveyed reach) as well as locations of supplemental point surveys. AL, refers to the reach immediately above the Lehigh River confluence; BL refers to reaches immediately below the Lehigh River confluence.

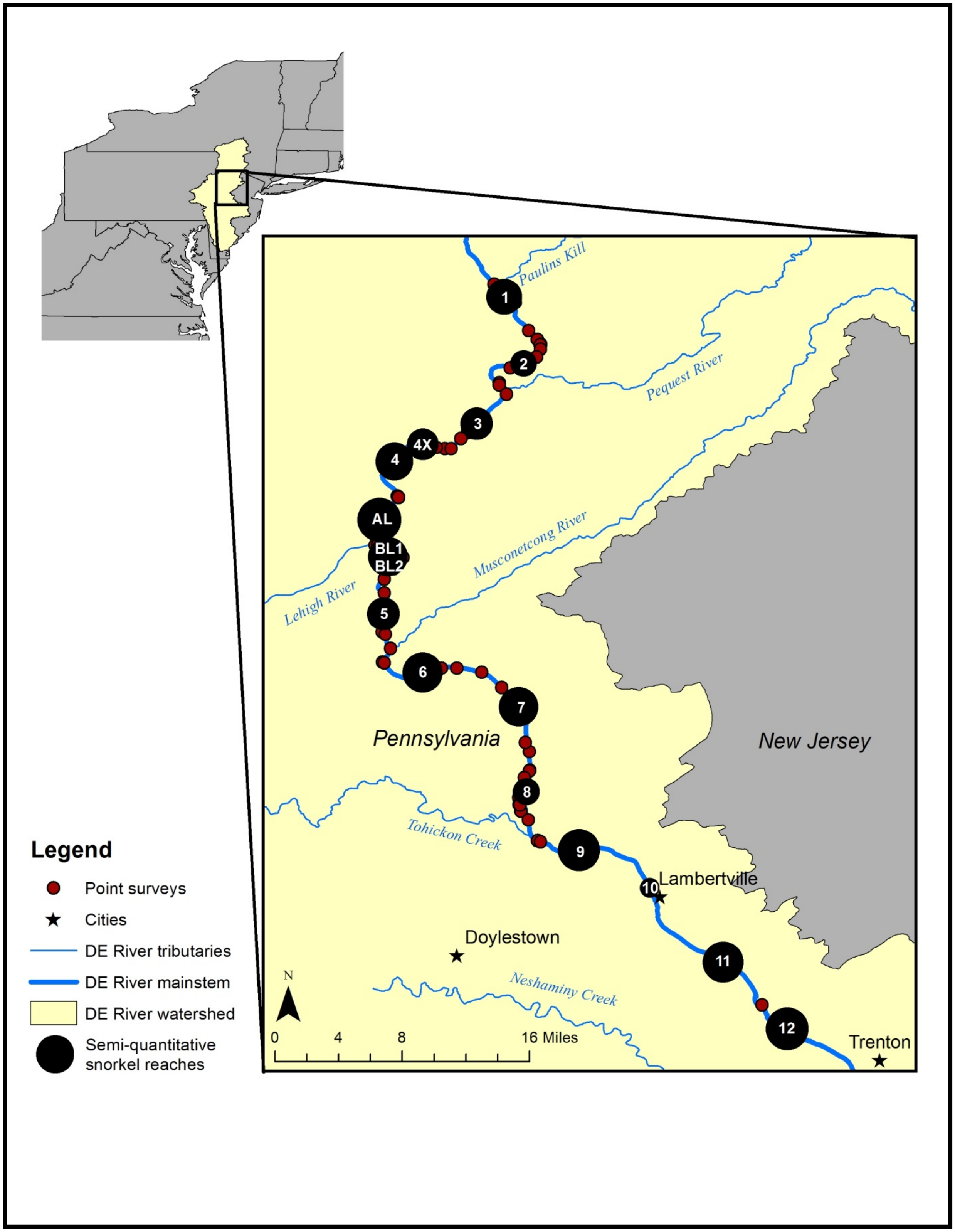

Figure 2. Catch per unit effort (CPUE; # mussels/hr) for each of the 12 randomized semi-quantitative sampling reaches for the 3 most common species in our surveys (location of the Lehigh River confluence indicated with dashed line).

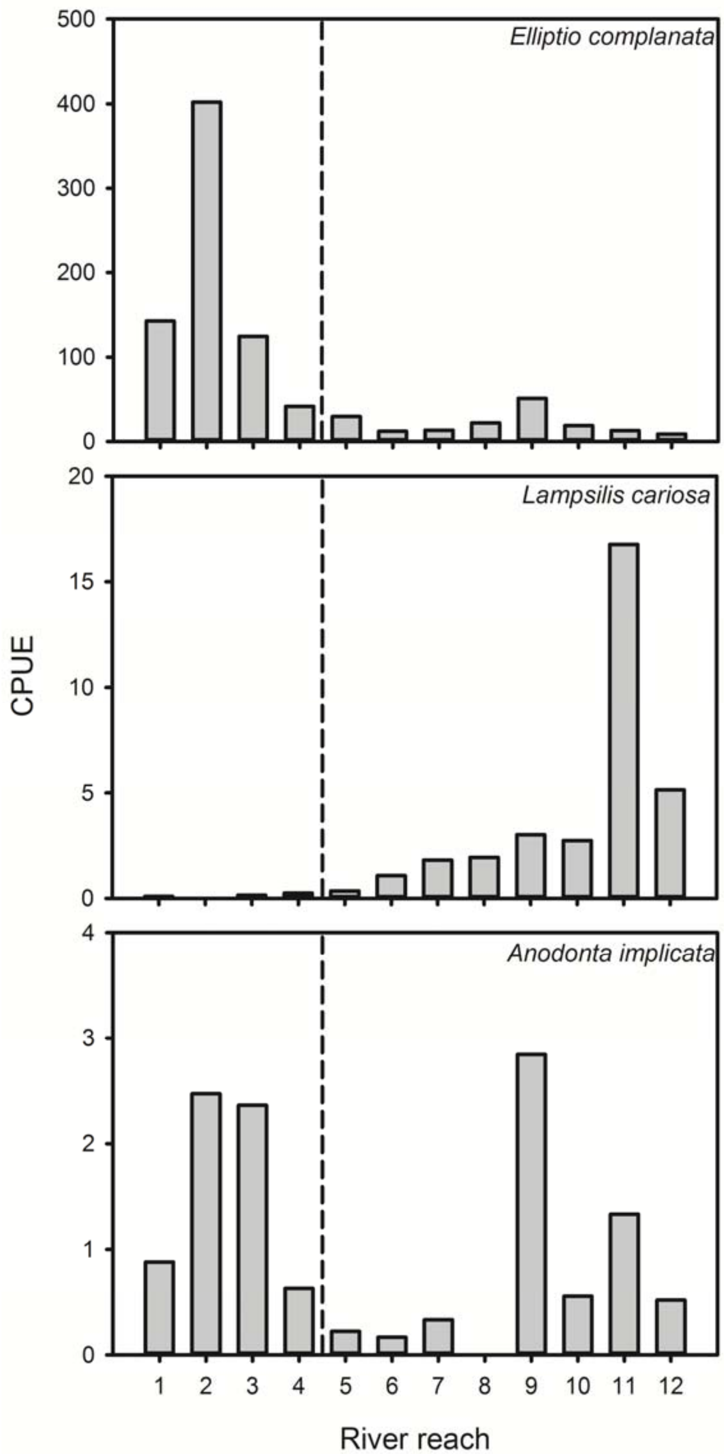

Figure 3. Raw counts of mussels per survey segment for the three common species, with kernal smoothing line shown for each graph (kernel smoother for conditional mean; Gaussian kernel; band width=10). Lehigh River confluence indicated by small red arrow at river mile 183.7.

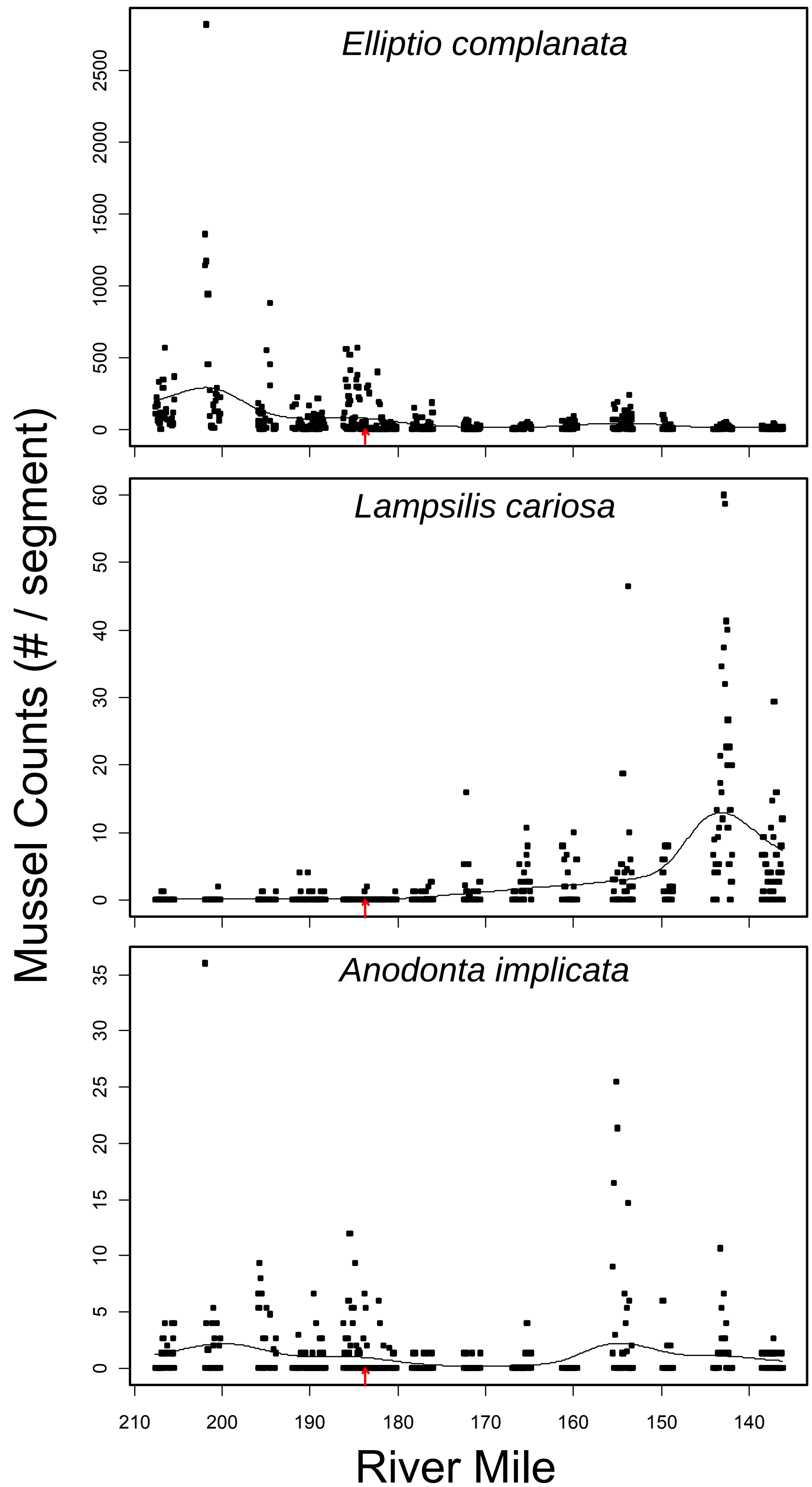

Figure 4. *Elliptio complanata* catch per unit effort (CPUE; # of mussels/hr) for individual segments relative to the Lehigh mixing zone (as measured by specific conductance), with mussel data plotted separately for the PA bank (upper panel) and the NJ bank (lower panel). Lehigh River confluence indicated by small red arrow at river mile 183.7.

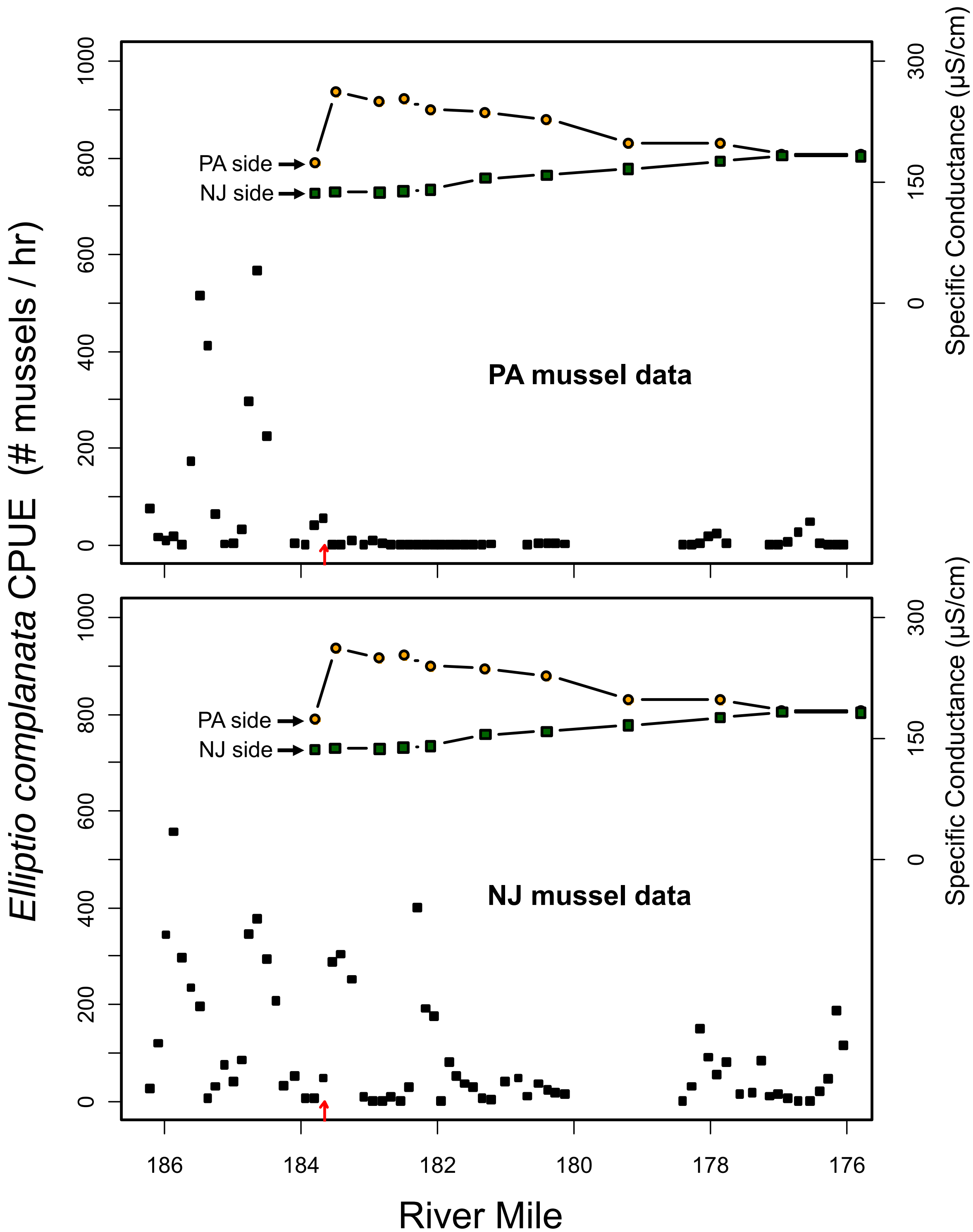

Figure 5. *Anodonta implicata* catch per unit effort (CPUE; # mussels/hr) for individual segments relative to the Lehigh mixing zone (as measured by specific conductance), with mussel data plotted separately for the PA bank (upper panel) and the NJ bank (lower panel). Lehigh River confluence indicated by small red arrow at river mile 183.7.

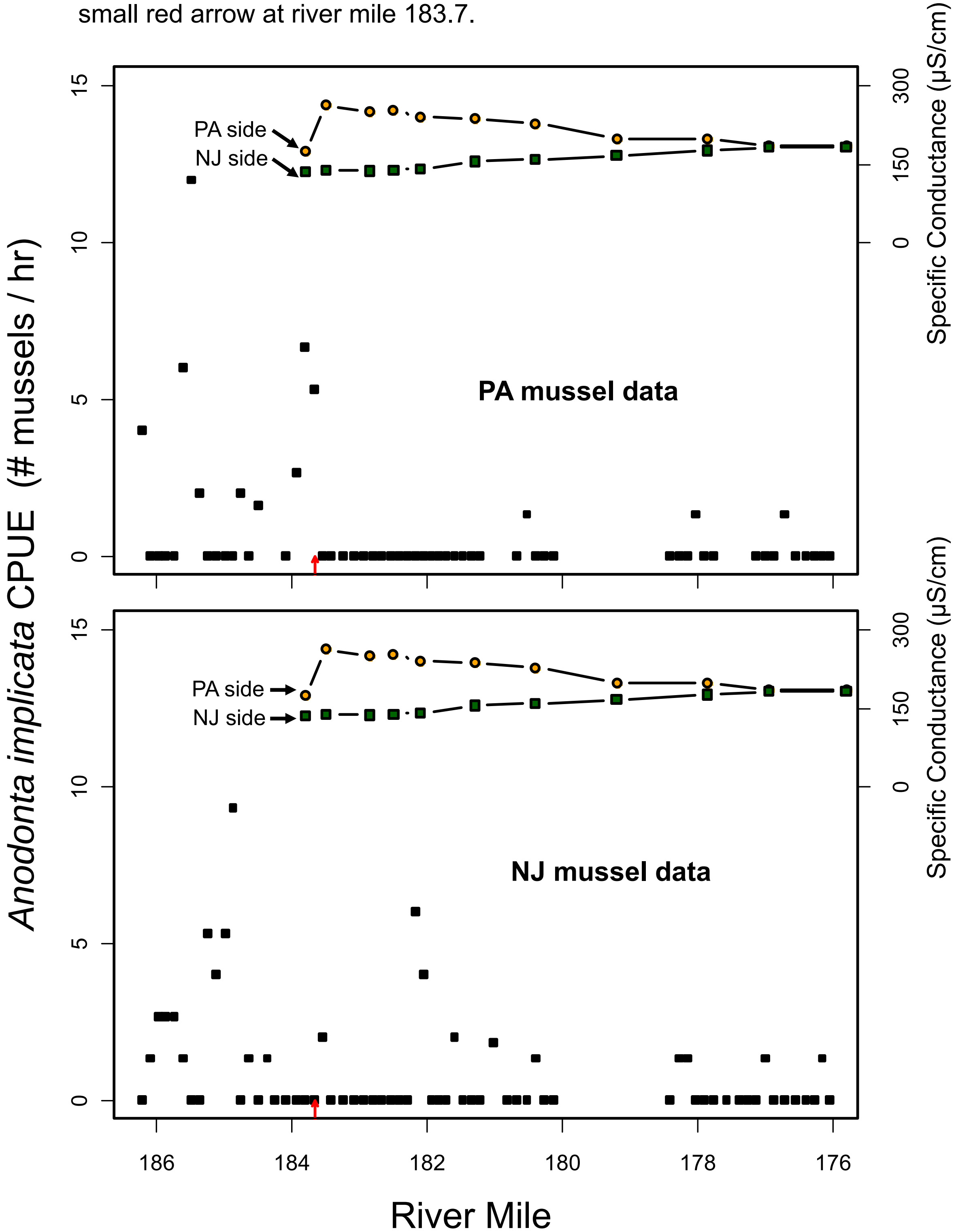

Figure 6. Catch per unit effort (CPUE; # mussels/hr) for ~200 meter length river segments in the Delaware Watergap (open squares; data from Lellis 2002) and the current Lower Delaware survey (filled circles). Data for the Delaware Watergap are provided as individual segment data across the entire river channel; Lower Delaware results combine data from both river banks (PA/NJ) into a single CPUE for each river segment surveyed. Lehigh River confluence indicated by small red arrow at river mile 183.7.

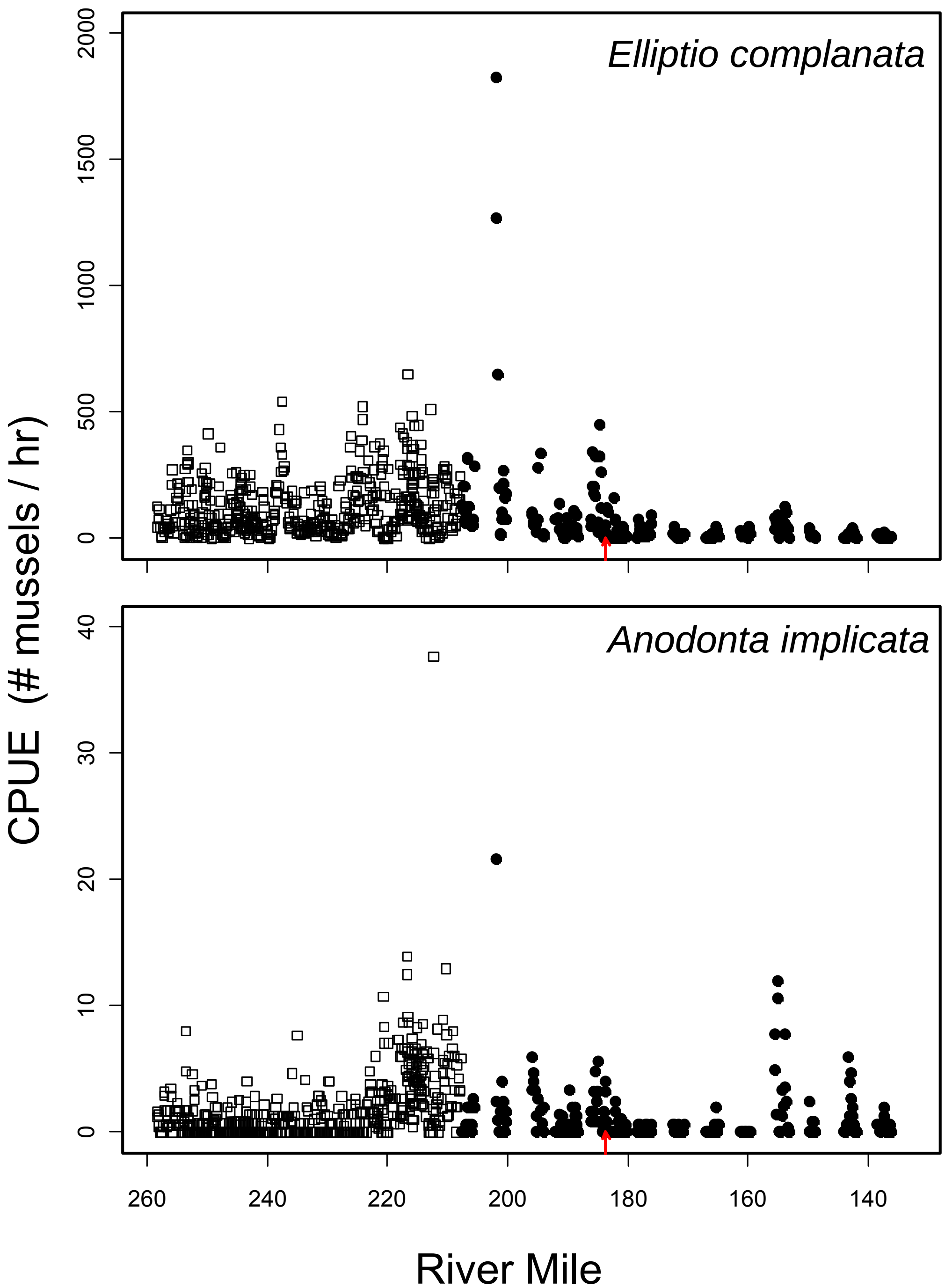

Table 1. Total individual mussels identified for each sample reach in the semi-quantitative snorkel surveys, along with general details for each reach. RM, river mile; Random, reaches randomly selected for survey; Targeted, additional reaches selected for survey.

Reach	"Random" or "T" (targeted)	RM Start	RM End	Miles Surveyed	Hours Surveyed	*Elliptio complanata*	*Lampsilis cariosa*	*Anodonta implicata*	*Pyganodon cataracta*	*Leptodea ochracea*	*Strophitus undulatus*	*Alasmidonta undulata*
1	Random	207.7	205.4	2.3	24.00	3366	2	22	1	0	1	0
2	Random	202.0	200.2	1.8	17.03	6864	1	47	79	0	0	5
3	Random	196.0	193.8	2.2	21.42	2800	3	52	2	0	0	0
4x (extra)	T	192.1	190.5	1.6	15.50	798	4	6	3	0	3	0
4	Random	190.5	188.2	2.3	28.25	1171	6	18	7	0	0	0
Above Lehigh	T	186.3	183.6	2.7	26.37	3826	1	53	28	0	0	0
Below Lehigh1	T	183.6	181.4	2.2	21.25	945	1	7	5	0	0	0
Below Lehigh2	T	181.4	180.0	1.4	13.58	205	1	4	0	0	0	0
5	Random	178.5	176.0	2.5	27.75	821	10	6	0	0	0	0
6	Random	172.5	170.5	2.0	31.65	405	34	5	2	0	0	0
7	Random	167.0	164.8	2.2	27.00	365	49	9	1	0	0	0
8	Random	161.3	159.6	1.8	11.90	259	23	0	0	0	0	0
9	Random	155.6	153.1	2.5	27.17	1507	84	86	30	0	1	0
10	Random	149.9	148.7	1.2	11.25	184	27	5	9	0	0	0
11	Random	144.2	141.8	2.3	27.50	356	456	36	9	0	0	0
12	Random	138.6	136.2	2.4	27.00	243	139	14	14	6	0	0
totals =	12 "R" / 4 "T"			33.3	358.62	24,115	841	370	190	6	5	5

Table 2. Catch per unit effort (CPUE; # mussels counted per hour of active survey time) for three most abundant mussel species in each sample reach. RM, river mile; Random, reaches randomly selected for survey; Targeted, additional reaches selected for survey.

Reach	"Random" or "T" (targeted)	RM average	CPUE for *Elliptio complanata*	CPUE for *Lampsilis cariosa*	CPUE for *Anodonta implicata*
1	Random	206.5	140.3	0.1	0.9
2	Random	201.1	403.0	0.1	2.8
3	Random	194.9	130.7	0.1	2.4
4x (extra)	T	191.3	51.5	0.3	0.4
4	Random	189.4	41.5	0.2	0.6
Above Lehigh	T	184.9	145.1	0.0	2.0
Below Lehigh1	T	182.5	44.5	0.0	0.3
Below Lehigh2	T	180.7	15.1	0.1	0.3
5	Random	177.2	29.6	0.4	0.2
6	Random	171.5	12.8	1.1	0.2
7	Random	165.9	13.5	1.8	0.3
8	Random	160.4	21.8	1.9	0.0
9	Random	154.4	55.5	3.1	3.2
10	Random	149.3	16.4	2.4	0.4
11	Random	143.0	12.9	16.6	1.3
12	Random	137.4	9.0	5.1	0.5

Table 3. Summary statistics (minimum, 25th and 75th percentiles, median, and maximum) of segment scale catch per unit effort (CPUE; # mussels/hr) for *Elliptio complanata*. Number of segments surveyed is the number of distinct segments quantified within each reach.

Reach	# of Segments Surveyed	Catch per Unit Effort (CPUE; # mussels / hr)				
		minimum	*25th percentile*	*median*	*75th percentile*	*maximum*
1	31	4.0	65.7	105.3	178.0	569.3
2	26	8.0	70.5	183.3	288.0	2816.0
3	27	0	7.3	46.7	125.3	877.5
4x (extra)	18	0	4.3	16.0	47.0	225.3
4	38	0	2.0	26.0	61.0	217.3
Above Lehigh	42	0	10.0	54.0	232.4	568.0
Below Lehigh1	34	0	0	1.3	34.0	400.0
Below Lehigh2	18	0	1.8	4.7	21.7	49.5
5	36	0	1.3	8.7	34.3	186.7
6	40	0	2.3	4.7	14.7	66.7
7	36	0	2.7	8.0	22.7	48.0
8	24	0	0	10.0	40.0	96.0
9	42	0	0.3	20.7	84.0	241.0
10	18	2.7	5.5	8.0	18.0	104.0
11	36	0	4.0	6.7	18.0	52.0
12	36	0	1.3	5.3	14.7	42.7

Table 4. Total individual mussels identified during supplemental point surveys, with results aggregated across point surveys conducted within the same reach.

Reach	# of Point Surveys	Hours Surveyed	*Elliptio complanata*	*Lampsilis cariosa*	*Anodonta implicata*	*Pyganodon cataracta*	*Leptodea ochracea*	*Strophitus undulatus*	*Alasmidonta undulata*	Total Mussels
1	3	6.00	187	0	0	0	0	1	0	188
gap - 1 to 2	5	2.17	61	0	1	0	0	1	0	63
2	3	4.00	57	0	0	0	0	1	0	58
gap - 2 to 3	3	1.75	14	0	1	0	0	0	0	15
3	3	2.92	106	0	0	0	0	0	0	106
gap - 3 to 4x	3	1.50	24	0	0	6	0	0	0	30
4x (extra)	3	1.50	32	0	0	0	0	0	0	32
4	0									
gap - 4 to Above Lehigh	3	1.25	175	0	0	0	0	0	0	175
Above Lehigh	2	0.50	208	0	0	0	0	0	0	208
Below Lehigh1	3	1.50	49	0	1	4	0	0	0	54
Below Lehigh2	1	0.50	1	0	0	0	0	0	0	1
gap - Below Lehigh2 to 5	2	1.00	2	0	0	0	0	0	0	2
5	2	1.00	0	0	0	0	0	0	0	0
gap - 5 to 6	5	2.50	35	1	0	0	0	0	0	36
6	2	1.00	8	0	0	0	0	0	0	8
gap 6 to 7	3	1.87	21	6	2	0	0	0	0	29
7	0									
gap 7 to 8	5	5.17	34	3	1	0	0	0	0	38
8	5	3.67	54	2	2	0	0	0	0	58
gap 8 to 9	3	1.30	1	0	0	0	0	0	0	1
9	0									
gap 9 to 10	0									
10	0									
gap 10 to 11	0									
11	0									
gap 11 to 12	1	1.50	19	16	0	0	0	0	0	35
12	0									
gap - below 12	0									
totals =	60	42.58	1088	28	8	10	0	3	0	1137

Table 5. Summary of specific conductance as a tracer for Lehigh River mixing into the Delaware River (see Appendix 2 for detailed results).

	Specific Conductance (µS/cm)	
River Mile (RM)	**PA side of river**	**NJ side of river**
183.78	174*	139
RM 183.64-183.72: Lehigh confluence		
183.49	263	138
182.85	251	141
182.53	253	139
182.07	240	141
181.30	237	155
180.36	228	159
179.21	199	166
177.84	198	178
176.95	185	183
175.82	185	182

* - localized influence of a small tributary (Bushkill Creek) with high specific conductance was measured near the Pennsylvania bank immediately upstream of the Lehigh confluence

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Appendices

Appendix 1. Data distributions for *Lampsilis cariosa* and *Anodonta implicata* catch per unit effort (CPUE; # of mussels/hr) among segments within each reach

Appendix 2. Raw specific conductance data throughout a select reach of the mainstem Delaware River delineating the mixing zone with the Lehigh River.

Appendix 1. Summary statistics (minimum, 25th and 75th percentiles, median, and maximum) of segment scale catch per unit effort (CPUE; # mussels/hr) for *Lampsilis cariosa and Anodonta implicata*. Number of segments surveyed is the number of distinct segments quantified within each reach.

		Lampsilis cariosa Catch per Unit Effort (CPUE; # mussels / hr)				
Reach	**# of Segments Surveyed**	***minimum***	***25th percentile***	***median***	***75th percentile***	***maximum***
1	31	0	0	0	0	1.3
2	26	0	0	0	0	2.0
3	27	0	0	0	0	1.3
4x (extra)	18	0	0	0	0	4.0
4	38	0	0	0	0	4.0
Above Lehigh	42	0	0	0	0	1.3
Below Lehigh1	34	0	0	0	0	2.0
Below Lehigh2	18	0	0	0	0	1.3
5	36	0	0	0	0	2.7
6	40	0	0	0	1.3	16.0
7	36	0	0	1.3	2.7	10.7
8	24	0	0	0	2.5	10.0
9	42	0	0	0	3.0	46.5
10	18	0	0	1.3	5.5	8.0
11	36	0	5.3	12.0	22.7	60.0
12	36	0	1.3	4.0	6.7	29.3

Appendix 1. Summary statistics (minimum, 25th and 75th percentiles, median, and maximum) of segment scale catch per unit effort (CPUE; # mussels/hr) for *Lampsilis cariosa and Anodonta implicata*. Number of segments surveyed is the number of distinct segments quantified within each reach (cont).

		Anodonta implicata **Catch per Unit Effort (CPUE; # mussels / hr)**				
Reach	**# of Segments Surveyed**	***minimum***	***25th percentile***	***median***	***75th percentile***	***maximum***
1	31	0	0	0	1.3	4.0
2	26	0	0	0	2.5	36.0
3	27	0	0	0	5.1	9.3
4x (extra)	18	0	0	0	1.0	3.0
4	38	0	0	0	0	6.7
Above Lehigh	42	0	0	0	2.7	12.0
Below Lehigh1	34	0	0	0	0	6.0
Below Lehigh2	18	0	0	0	0	1.8
5	36	0	0	0	0	1.3
6	40	0	0	0	0	1.3
7	36	0	0	0	0	4.0
8	24	0	0	0	0	0
9	42	0	0	0	1.9	25.5
10	18	0	0	0	0	6.0
11	36	0	0	0	1.3	10.7
12	36	0	0	0	1.3	2.7

Appendix 2. Raw specific conductance data, and location information, throughout a select reach of the mainstem Delaware River delineating the mixing zone with the Lehigh River.

	PA (near shore)		mid-way between PA & center		center		mid-way between NJ & center		NJ (near shore)		
River Mile	Sp.Cond	temp (C)	Sp.Cond	temp (C)	Sp.Cond	temp (C)	Sp.Cond	temp (C)	Sp.Cond	temp (C)	**Landmarks**
183.95	233	19.7	190	20.2	136	20.8	136	20.7	143	20.7	near Route 22 bridge
183.78	174	20.3	168	20.5	149	20.7	136	20.8	139	20.8	below Northampton St bridge
183.49	263	19.3	237	19.6	166	20.7	142	20.9	138	20.8	1st transect below Lehigh confl & below RR bridge
182.85	251	19.6	230	19.8	170	20.8	137	21.0	141	21.0	above WWTP
182.53	253	19.8	202	20.2	153	20.8	139	21.0	178*	21.7	below WWTP
182.07	240	19.9	230	20.0	202	20.3	154	20.9	141	21.1	above Lopatcong confluence
181.30	237	20.6	209	20.2	184	20.6	162	20.8	155	20.9	below I-78 bridge
180.36	228	20.9	207	20.5	188	20.6	164	20.8	159	20.8	above Whippoorwill Is
179.21	199	20.7	189	20.7	186	20.7	171	20.8	166	20.9	above Old Sow Is
177.84	198	21.1	189	21.0	183	21.0	176	21.1	178	20.9	just above Raubs Is
176.95	185	21.2	185	21.1	183	21.1	183	21.0	183	21.0	below Raubs Is
175.82	185	21.3	184	21.2	183	21.1	183	21.1	182	21.2	above Reigelsville
174.90	190	21.3	185	21.3	183	21.2	183	21.2	184	21.4	below Reigelsville bridge / above Musc. confl.
174.00	188	21.4	184	21.4	184	21.3	201	21.2	219	21.2	above Cooks Cr
172.64	184	21.5	185	21.4	185	21.3	200	21.4	211	21.5	above Lynn Is
171.56	183	21.9	183	21.5	184	21.5	185	21.5	207	21.8	right below Gilbert Power Plant
170.73	185	22.0	186	21.6	186	21.6	191	21.5	205	21.7	under powerlines
169.98	184	22.0	185	21.6	187	21.6	195	21.6	202	22.1	below riffle
169.49	187	22.0	187	21.8	188	21.6	194	21.6	203	22.1	in sight of Milford bridge
168.28	186	21.9	187	21.9	188	21.7	193	21.7	199	22.2	below Milford bridge

* - near-bank rise in conductivity was not representative of NJ half of river; "mid-way between NJ & center" conductivity value used for Table 2 of report

Appendix 2. Raw specific conductance data, and location information, throughout a select reach of the mainstem Delaware River delineating the mixing zone with the Lehigh River (cont.).

	PA (near shore)		mid-way between PA & center		center		mid-way between NJ & center		NJ (near shore)		
River Mile	lat	long	lat	long	lat	long	lat	long	lat	long	**Landmarks**
183.95	40.69356	-75.20435	40.69353	-75.20424	40.69346	-75.20390	40.69350	-75.20367	40.69353	-75.20338	near Route 22 bridge
183.78	40.69079	-75.20461	40.69086	-75.20443	40.69088	-75.20411	40.69085	-75.20372	40.69353	-75.20338	below Northampton St bridge
183.49	40.68686	-75.20283	40.68689	-75.20247	40.68694	-75.20200	40.68698	-75.20153	40.68710	-75.20112	1st transect below Lehigh confl & below RR bridge
182.85	40.68004	-75.19454	40.68014	-75.19447	40.68030	-75.19434	40.68058	-75.19421	40.68079	-75.19405	above WWTP
182.53	40.67905	-75.18854	40.67923	-75.18857	40.67951	-75.18859	40.67973	-75.18861	40.67999	-75.18854	below WWTP
182.07	40.67876	-75.18050	40.67893	-75.18040	40.67917	-75.18025	40.67939	-75.17992	40.67958	-75.17963	above Lopatcong confluence
181.30	40.67023	-75.18022	40.67011	-75.18011	40.66996	-75.17986	40.66986	-75.17962	40.66955	-75.17950	below I-78 bridge
180.36	40.66088	-75.19297	40.66073	-75.19267	40.66042	-75.19233	40.66026	-75.19194	40.66010	-75.19157	above Whippoorwill Is
179.21	40.64511	-75.19914	40.64531	-75.19897	40.64552	-75.19872	40.64578	-75.19843	40.64598	-75.19820	above Old Sow Is
177.84	40.62724	-75.19030	40.62729	-75.18994	40.62736	-75.18947	40.62741	-75.18900	40.62741	-75.18848	just above Raubs Is
176.95	40.61973	-75.19730	40.61955	-75.19720	40.61914	-75.19718	40.61872	-75.19702	40.61850	-75.19692	below Raubs Is
175.82	40.60587	-75.19588	40.60592	-75.19558	40.60614	-75.19510	40.60639	-75.19466	40.60656	-75.19444	above Reigelsville
174.90	40.59303	-75.19109	40.59307	-75.19077	40.59323	-75.19040	40.59335	-75.18991	40.59337	-75.18947	below Reigelsville bridge / above Musc. confl.
174.00	40.58107	-75.19612	40.58097	-75.19582	40.58080	-75.19537	40.58077	-75.19492	40.58086	-75.19450	above Cooks Cr
172.64	40.56538	-75.17889	40.56559	-75.17857	40.56594	-75.17840	40.56636	-75.17824	40.56675	-75.17822	above Lynn Is
171.56	40.56533	-75.15685	40.56554	-75.15700	40.56586	-75.15726	40.56613	-75.15739	40.56660	-75.15759	right below Gilbert Power Plant
170.73	40.57341	-75.14430	40.57369	-75.14442	40.57406	-75.14452	40.57460	-75.14472	40.57488	-75.14499	under powerlines
169.98	40.57419	-75.12994	40.57441	-75.12972	40.57473	-75.12973	40.57511	-75.12970	40.57542	-75.12968	below riffle
169.49	40.57320	-75.12006	40.57341	-75.12004	40.57373	-75.11996	40.57406	-75.11993	40.57450	-75.11997	in sight of Milford bridge
168.28	40.56544	-75.09876	40.56567	-75.09801	40.56598	-75.09801	40.56617	-75.09760	40.56647	-75.09718	below Milford bridge